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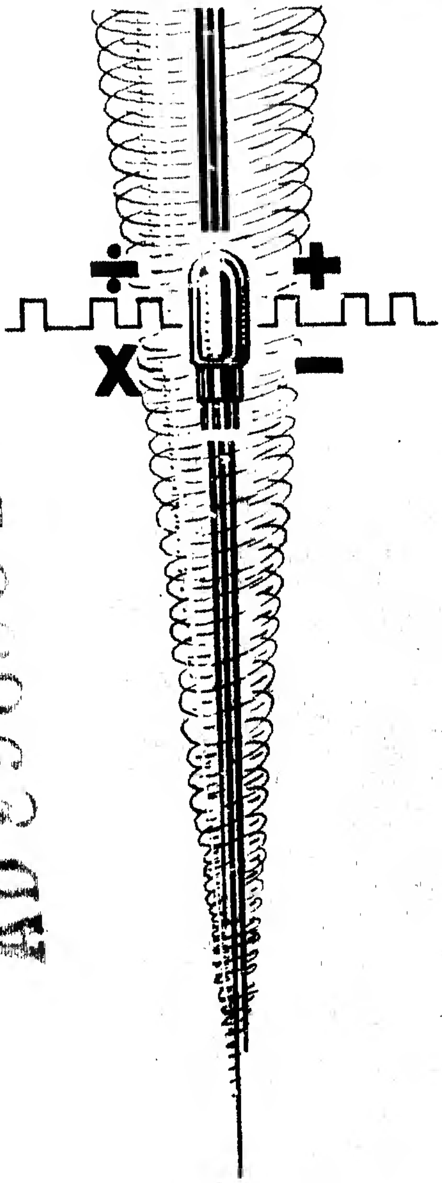

PROJECT WHIRLWIND

Contract N5ori60

SUMMARY REPORT NO. 2

VOLUME 14

AIRCRAFT SIMULATION

SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SPECIAL DEVICES CENTER

(1)

(9) ~~PROJECT WHIRLWIND~~
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AIRCRAFT SIMULATION.

Volume 14 of 22 Volumes

(15) N5ori-60.

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

CONTENTS

INTRODUCTION

The initial objective of Project Whirlwind was to simulate the flight characteristics of an aircraft with the aim of obtaining pilot reaction to a proposed aircraft based on wind tunnel data without first going to the expense of building a prototype. The simulator could also be used to evaluate the desirability of proposed changes in an existing aircraft. A computer would have stored in it a program for the solution of the equations of motion of an aircraft, and the function tables representing the characteristics of a particular aircraft based on wind tunnel data. Inputs to the computer would be the pilot's control motions; outputs would be the appropriate instrument readings and quantities representing the forces on the pilot and on the controls. This is quite fully described in Summary Report No. 1 which is Vol. 3 of this series. Report R-64-1, which is Appendix A of Summary Report No. 1, presents a form of these equations as worked out by the staff of the Aeronautical Engineering Department at M.I.T. in co-operation with Project Whirlwind. This form of the equations is capable of digital solution and the variable coefficients can, in general, be measured in existing wind tunnels. An extension of wind tunnel techniques is underway to measure the rotary derivatives. Certain modifications have been made in the equations and functions since publication of R-64-1. In particular, a transformation of axes has been made which alters the form of equations (4), (5), (6), (13), (14), (15) and eliminates the necessity for repeatedly solving equations (16), (17) and (18). Independently of this, the number of variables in some of the coefficients has been reduced.

R-103 is an analysis of the functions in the aircraft equations of R-64 with particular reference to a typical aircraft described in R-98. It determines the storage capacity necessary in the computer to describe the aircraft, and shows the relative interpolation time devoted to various computed quantities.

C-15 is an extension of this to indicate the necessary computing speed. The coding described in C-15 was done for a serial computer and used an integration method which must be revised. However, the results can be directly interpreted in terms of a parallel computer.

M-65 discusses the abilities of the Whirlwind I computer to handle the aircraft simulation problem. Further work indicates that the Whirlwind I computer could give a reasonable representation of the motion of the aircraft about all three axes provided some rather severe restrictions were imposed on speed range, angle of attack, angular velocities and control motions.

Cockpit design is in progress. Firm decisions on all of the questions of design have not yet been made. In order to obtain valid pilot reaction to evaluate simulated aircraft, the cockpit must be capable of producing a realistic sensation of flight and accurate simulation of aircraft behavior as normally perceived by the pilot. Simultaneously, the pilot's actions in controlling the simulated aircraft must be transmitted to the computer.

Accurate simulation of aircraft behavior is transmitted to the pilot as 1) control-force loading or control "feel", 2) noise and vibration, 3) correct indication of all instrument, 4) duplication of the appearance of the actual aircraft interior, and 5) simulated acceleration produced by cockpit motion. The general approach to the problem described in R-125 has been to develop equipment to duplicate aircraft appearance and behavior, except in the case of cockpit motion where exact duplication is impractical.

A test model of the control-force loading servomechanism for elevator forces has been constructed as described in R-36. Tests of this equipment show that it is very nearly satisfactory, and work is under way to improve its speed of response. The simulation of elastance, backlash, and coulomb friction in aircraft controls will be necessary. Mechanisms for inserting these quantities in the control linkages have been designed, and studies are being carried out to determine the feasibility of an alternate method of inserting these quantities by means of the computer and the control-force loading servos.

Noise and vibration generators have not been studied, since suitable simulation has been accomplished in some Navy Operational Flight Trainers, see R-125.

The design of the pilot's instrument panel has been started. The less precise instruments will be voltmeters and the faster, more precise instruments will be servomechanisms receiving data from the computer (M-74 and R-125).

Studies of cockpit mounting and motion have been made and are reported in R-100 and R-125. At best, cockpit motion can only approximate the accelerations applied to the pilot. Since the necessity for cockpit motion has not been established, and since the present building facilities will not allow sufficient cockpit motion, this phase of Whirlwind I design of the first cockpit has been discontinued.

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Report 49

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: May 10, 1945

Subject: Numerical Ranges for ASCA (Revised Estimate - May 9, 1945).

References: Original Copy - J. W. Forrester's file;
Authors: L. Bernbaum) - both of WBWT.
J. Bicknell)

Conclusion: The following data and estimates are reproduced below exactly as submitted by the staff of WBWT, M.I.T., on May 9, 1945.

Revised Estimates of Numerical Ranges for ASCA
(Instead of ranges of areas, lengths, weights, etc., certain parameters were set up where possible.)

1. Mass and Inertia Terms

	Limits	
m - mass - slugs	200	7000
$\frac{S}{m} = \frac{\text{area}}{\text{mass}} = \frac{\text{ft.}^2}{\text{slug}}$	.25	2.0
$\bar{a}$ - moment of inertia coef. (x axis)	.005	.05
$\bar{b}$ - " " " " (y axis)	0*	.05
$\bar{c}$ - " " " " (z axis)	.005	.05

* - Moment of inertia about the y axis may be zero or very nearly so for a flying wing. (Coefficients are based on span.)

2. Length Ratios

$\frac{c}{b}$ - ratio of chord to span	1	15.
b - span, ft.	35	300
$\frac{y_1}{b} = \frac{\text{dist. from fus. ℄ to outb'd eng. ℄}}{\text{span}}$	0	.5
$\frac{y_2}{b} = \frac{\text{dist. from fus. ℄ to inb'd eng. ℄}}{\text{span}}$	0	.4

		Limits	
2. Length Ratios (Cont.)			
C.G. Movement			
D/C along oz		-.2	+.2
G/C along oy		-.2	+.2
H/C along oz		-.75	+.25
3. Control Surface Dimensions			
Aileron	S_A - ft.^{2}	22	700
	C_A - ft.	1	5
Elevator	S_E - ft.^{2}	34	600
	C_E - ft.	2.5	12
Rudder	S_R - ft.^{2}	17	400
	C_R - ft.	2.5	10
4. Reference Angles (Degrees)			
Θ		-60	+60
ψ		0	360
φ		-75	+75
α		-20	+40
γ		-40	+40
ε		-15	+10
Θ_o		-10	+20
5. Control Surface and Tab Deflections			
δ_E		-30	+20
δ_A		-30	+30
δ_R		-30	+30
δ_{E_t}		-20	+20
δ_{A_t}		-20	+20

		Range	
5.	Control Surface and Tab Deflections (Cont.)		
	δ_{E_t}	-20	+20
	δ_F	0	60
6.	Miscellaneous Deflections		
	L_G - landing gear	0	100%
	C_F - cowl flaps	0	50°
	D_D - bomb door	0	100%
7.	Linear Velocities		
	V - velocity along flight path (0 g) (m.p.h.)	0	+600
	u - velocity along ox	0	+600
	v - velocity along oy	-200	+200
	w - velocity along oz	-100	+100
8.	Linear Accelerations (Along Wind Axes)		
	$\frac{\lambda}{m}$	+5 g	-10 g

Estimated from maximum allowable loads. Large airplanes are designed for a load condition of -4 g. Pilot cannot take more than -10 g except for extremely short intervals. Maneuvers to give a positive acceleration are not common. +5 g should cover all conditions.

	$\frac{A}{m}$	0	-2.0 g

The maximum acceleration along the ox axis due to aerodynamic effects alone is estimated as -2 g assuming flaps can be fully deflected (C_D = .4) instantaneously at a speed of 200 m.p.h. for a W/S = 20 lbs./sq. ft. It is expected that drag increases due to Mach number effects will not give a deceleration of the above magnitude.

	$\frac{T}{m}$	2.5 g	-1 g

1 g is estimated for a rocket assist take-off at 80 m.p.h. in 4 seconds. 2.5 g is estimated for a catapult take-off at 60 m.p.h. in 60 ft. (for small airplanes). -1 g is estimated for reversible thrust props.

8. Linear Accelerations (Along Wind Axes) (Cont.) Axis

$\frac{F}{m}$ ±.5 g ±2.5 g

±2.5 g is based on a maximum side force coefficient of .5 suddenly attained by yawing a 20 lb./ft. wing loaded airplane 20° when flying at 200 m.p.h.

9. Angular Velocities (rad/sec)

a. Measured on

	SB2C-1	C-46	B-26B-21	P-38
p	.9	.4	.5	2.5
q	.5	.2	.3	
r		.2	.15	
W/S, lbs./ft.^{2}	29.5	33.0	47.0	30 approx.

b. Obtainable The accelerations and velocities will be inversely proportional to the wing loading, W/S. For an airplane like the B-26B-21 with a decreased W/S = 20 lbs./ft.^{2}, the velocities would be:

$p = 1.25$

$q = .75$

$r = .37$

c. Possible By forcing the motion, i.e., applying left and right rudder alternately, the velocities might be doubled.

$p = 2.5$

$q = 1.5$

$r = .75$

d. Design Maximum for ASCA Since an r = q was measured on the C-46, and adding a margin of safety:

$p = \pm 4.0$ rad/sec

$q = \pm 2.0$ rad/sec

$r = \pm 2.0$ rad/sec

9. Angular Velocities (rad/sec) (Cont)

The rates of change of earth reference angle are then, by resolving:

$\dot{\psi} = \dot{r} \quad \pm 3.0$ rad/sec

$\dot{\phi} = \quad \pm 5.0$ rad/sec

$\dot{\theta} = \dot{\alpha} \quad \pm 3.0$ rad/sec

10. Angular Accelerations (rad/sec^2)

a. Measured on

Measured on	SB2C-1	C-46	B-26B	P-38
$\dot{p}$	1.4	.8	1.2	6
$\dot{q}$	1.4	.4	.3	
$\dot{r}$		.05	.2	
W/S	29.5	33.0	47.0	~ 30

b. Obtainable For the B-26B with a theoretical wing loading of 20 lbs./ft.:

$\dot{p} = 2.8$

$\dot{q} = .7$

$\dot{r} = .5$

c. Possible By forcing the motion, the accelerations might be doubled:

$\dot{p} = 5.6$

$\dot{q} = 1.5$

$\dot{r} = 1.0$

d. Design Maximum for ASCA Including a margin of safety added to the accelerations that are possible, the following are suggested:

$\dot{p} \quad \pm 7$ rad/sec^2

$\dot{q} \quad \pm 3$ rad/sec^2

$\dot{r} \quad \pm 2$ rad/sec^2

11. Stick and Pedal Loads

The following are 2.5 times the limit of the average pilot's strength and should be considered as the maximum loads to reach the controls. A control system with a boost can be represented by incorporating it into the machine before the final control loads are computed.

		Pos.	Neg.
E_P	Elevator Control Force (lbs.)	750	750
A_P	Aileron Control Force "	300	300
R_P	Rudder Control Force "	1125	1125

12. Aerodynamic Coefficients

		Pos.	Neg.
C_L	Lift Coefficient	3.0	-1.0
C_D	Drag Coefficient	.01 to .4	
C_Y	Side Force Coefficient	.5	.5
C_m	Pitching Moment	.5	.5
C_n	Yawing Moment	.07	.07
C_ℓ	Rolling Moment	.1	.1

13. Hinge Moment Moduli

		Pos.	Neg.
K_{H_E}	Elevator H. M. Mod. (ft.^{3})	200	200
K_{H_A}	Aileron H. M. Mod. "	200	200
K_{H_R}	Rudder H. M. Mod. "	120	120

14. Control Surface Linkage Factors

These factors are not necessarily constants but have average values within the range given:

K_E	Elevator (ft/rad)	1.0	5
K_A	Aileron (rad. of wheel/rad. ail.)	1.0	10
K_R	Rudder (ft/rad)	1.0	2.5

Units Desired

α, β	Should be in degrees, because the tunnel data from which functions of α and β have been determined are in degrees.
$\dot{\alpha}$, $\dot{\beta}$	Should be in radians per second.
δ_A, δ_R, δ_E, δ_{Atab}, etc.	Control surface deflections should be in degrees.
φ, Θ, ψ	Earth angles should be recorded in degrees, but may be handled in the analyzer as radians.
p, q, r	Body axes velocities; radians per second are recommended.
μ	Ball bank angle, degrees.
u, v, w, V	Velocities can be handled in the analyzer in feet per second units. On the air speed meter they should be miles per hour. On the recorder V should be in miles per hour.
a_z	Normal accelerations on the recorder should be in g units.

Written by: WBWT Group

Engineer in charge H R Boyd

hrb-jlb

6395

Report 63

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: September 18, 1945

Subject: ASCA Conference, September 14, 1945

The people attending this conference were:

J. W. Forrester	E. Hollnagel
J. Bicknell	H. MacKachnie
L. Bernbaum	W. Loud
J. Ludwig	R. Brown
M. Witunski	M. Florencourt
H. Boyd	B. Drisko
R. Everett	M. Pierce
	S. Dodd

Take-off and Landing

Additions to the original take-off and landing specifications were recommended by J. Bicknell. He recommended that the rolling moments should be computed during take-off, but no effect of this rolling moment was to be felt until the plane had left the ground.

Screen for Visual Take-off

It was decided that a screen for visual take-off was not to be included as a part of the analyzer, but provisions were to be made so that a screen could be easily added.

Stall Representation

(a) No accuracy beyond stall point
(b) Increase or add rolling and yawing moments
(c) Reduce lift
(d) Problem of returning to lift curve must be settled
(e) Buffeting to be added on controls

Compressibility Effects in Auxiliary Equations

(a) Compressibility effects near or above sound velocity can be included by considering the Mach number.
(b) This Mach number is like the other non-linear data and could be added later if desired.

Rate of Climb Meter

(a) Should have a lag to simulate actual instrument
(b) Other instruments o.k.
(c) Should there be a Northerly turn error added to Compass?

Cockpit Instruments

(a) Manifold Pressure
(b) Engine RPM(built-in synchroscopes)
(c) Artifical Horizon
(d) Air Speed
(e) Turn and Bank
(f) Gyro Compass
(g) Blind Landing Instrument
(h) Remote Flux-gate Compass
(i) Rate of Climb
(j) Altimeter(both pressure and radio)
(k) Suction Gauge
(l) Clock
(m) Increase, Decrease Lights for Propeller Governor
(n) Wing Flaps and Landing Gear Indicator
(o) Outside Air Temperature
(p) Cylinder Head Temperature

Engineer's Panel

The possibility of one panel for the flight engineer and instructor was discussed. The opinion seemed to be that one man could perform both duties.

Automatic Pilot

Provision for an automatic pilot must be made, but it might be added later.

Deflection of Aircraft

(a) Deflection of fuselage and wings reduce the effect of the control surfaces.
(b) Drop in expected roll moment is about 10%.
(c) Ailerons will not require extra calculations.
(d) Stabilizer requires extra calculations
(e) J. Bicknell thinks it should go in

Equations of Motion

These do not allow more than approximately ± 70° of continuous motion. This is considered acceptable.

Center of Gravity Shifts

C.G. shifts should be possible. Changes of moments of inertia were discussed and probably will be included.

Instructor's and Operator's Panel

The instructor will probably also act as flight engineer. He should be able to change the following while the airplane is in flight:

(a) Change C.G.
(b) Disable engines and propellers
(c) Change mass and moments of inertia
(d) Introduce gusty or rough air
(e) PB4Y now has changes due to rought air in the roll only, which Lt. Ludwig feels is more realistic than the PBM representations.

Ground Track Recorder

(a) This should be added.
(b) Lt. Ludwig will supply a crab or cross arm flight recorder.
(c) May be controlled by instructor

Radio

A dummy radio set furnished with cockpit should be included to allow simulated landing by radar.

Wind Effects

No wind effects will be included except rough air.

Cockpit Motion

(a) Cockpit should tilt and pitch.
(b) Cockpit should probably be mounted on springs but a gimbel system might be used.

Vibration and Noise

(a) Must be added
(b) Generalized for 4-engine plane
(c) Should be easy to adjust frequency and amplitude of vibration

Control System

(a) Represent friction, inertia, and stretch in cables
(b) Put in coupling between plane and control surfaces.
(c) The oscillations of the control surfaces due to the inertia of the control surfaces, and the control system, and the stretch in the control cables, was felt to be of relatively high frequency and the possibility of including these effects with the present force loading equipment was questioned.

Written by: S H Dodd

Approved: Jay W Forrester

6345
ENGINEERING NOTES NO. 7

TO: Engineers of Project 6345 Page 1 of 1 page

FROM: Peter D. Tilton

SUBJECT: Additional Symbols Required for ASCA

DATE: February 26, 1946

REFERENCE: 6345 - Report 64

A preliminary investigation of the recording of information provided by the Flight Analyzer has shown the necessity for obtaining records of some quantities pertinent to stability flight testing which have not been included in the Table of Symbols of Report 64. These following quantities will be required as outputs from the computer, and have been designated by symbols consistent with those now used in the normal stability flight test reports. (See NACA confidential reports on Stability and Control Characteristics of XB-17F, SB2C-1, and C-46 Airplanes)

C.G. - Center of gravity position on longitudinal (OX) axis, expressed in percent of Mean Aerodynamic Chord (% M.A.C.)

F_S - Stick or control column force

F_R - Rudder pedal force

F_W - Aileron wheel force

V_c - Calibrated air speed, same as Air Speed Meter Reading given by Eq. 49

δA - Total aileron angle, equal to $\delta A_R + \delta A_L$

t - Time

It will be noted that C.G. can be calculated from a given design and hypothetical loading and can be related to the reference point through the variable H. (See Figure 4, Report 64).

The forces exerted on the controls by the pilot should be measured at the controls by strain gages and should be converted to binary numbers for recording.

The last three quantities defined represent nothing new, but are merely supplied with suitable symbols for convenience.

Engineer, P. D. Tilton

Approved:

PDT:hao

6345
Report No. R-98

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Mass.

Date of Report: March 7, 1946

Written by: S. H. Dodd

Subject: Constants and curves for a Twin Engine Airplane (called Model A) for Analyser Equations.

The information in this report was supplied by the WBWT in January 1946 as a typical aircraft analyzer problem. The functions and constants are for the most part, defined in Report 64.

The following constants are listed for reference.

$\bar{a}$	moment of inertia coefficient - OX axis	.0155
$\bar{b}$	" " " " - OY axis	.0140
$\bar{c}$	" " " " - OZ axis	.0395
w	airplane weight (cruise condition)	68,350 lbs.
m	airplane mass	2120 slugs
S	wing area	1400 sq. ft.
b	wing span	114 ft.
c	mean aerodynamic chord	12.52 ft.
y_2	distance from fuselage centerline to nacelle centerline	12.7 ft.
H	distance from reference point to c.g. along OX	0
H'	distance from reference point to point of main wheel contact along OX	-3 ft.
D	distance from reference point to c.g. along OZ	0
D'	distance from reference point to point of main wheel contact along OZ	8.5 ft.
G	distance from reference point to c.g. along OY	0
G'	main wheel tread	31.5 ft.
μ	ground coefficient of friction	.05
A	engine displacement	4360 cu. in.

D_p	propeller diameter	15.67 ft.
θ_o	ground angle	0°
Ψ_o	heading	0°
K_a	increase in ground coefficient of friction due to braking	0.5
K_b	$2 \times I_p \times 2\pi$ where I_p is moment of inertia of one propeller	
	$I_p = m_p K_p^2 = \frac{300}{322} (3.5)^2$	1435 slug ft.^{2}
K_1	increase in elevator contribution to C_L due to power from engines 2 and 3	2.0
K_2	ΔC_D from fully deflected cowl flaps - engine 1	0
K_3	ΔC_D " " " " " - engine 2	0.005
K_4	ΔC_D " " " " " - engine 3	0.005
K_5	ΔC_D " " " " " - engine 4	0
K_6	ΔC_D from fully deflected landing gear	0.025
K_7	ΔC_D from fully deflected bomb bay door	0.012
K_8	$\frac{\Delta C_F}{\Delta T_{c_2}'}$ at $\gamma = 0^{\circ}$	0
K_9	$\frac{\Delta C_F}{\Delta T_{c_3}'}$ at $\gamma = 0^{\circ}$	0
K_{10}	$\frac{\Delta dC_F/d\gamma}{\Delta \delta}$ change in basic side force slope with δ	-0.0001
K_{11}	$\frac{\Delta dC_F/d\gamma}{\Delta \delta_F}$ change in basic side force slope with δ_F	0

K_{12}	increase in rudder contribution to C_N due to power from engine 2	1.0
K_{13}	increase in rudder contribution to C_N due to power from engine 3	1.0
K_{15}	$\dfrac{\Delta C_m}{\Delta T_{c_1}}$	0
K_{16}	$\dfrac{\Delta C_m}{\Delta T_{c_4}}$	0
K_{17}	$\dfrac{\Delta C_m}{\Delta \delta_{E_t}}$	-0.001
K_{18}	$\dfrac{\Delta C_m}{\Delta \delta_{A_L}}$	-0.001
K_{19}	$\dfrac{\Delta C_m}{\Delta \delta_{A_R}}$	-0.001
K_{20}	ΔC_m from fully deflected cowl flaps - engine 1	0
K_{21}	ΔC_m " " " " " - engine 2	0.005
K_{22}	ΔC_m " " " " " - engine 3	0.005
K_{23}	ΔC_m " " " " " - engine 4	0
K_{24}	ΔC_m from fully deflected landing gear	-0.015
K_{25}	ΔC_m from fully deflected bomb bay doors at $\alpha = 0°$	-0.010
$K_{25.1}$	$\Delta \dfrac{dC_m}{d\alpha}$ from fully deflected bomb bay doors	+0.0015
$K_{26.2}$	$\dfrac{\Delta C_n}{\Delta \delta_{R_t}}$	.00015

K_{27}	change in basic yawing moment slope for fully deflected bomb doors	✓ 0.00013
$K_{27.1}$	constant for aileron divergence term	≈ 0.1
K_{28}	$\dfrac{\Delta C_{\ell}}{\Delta T_{c_1}'}$ at $\delta = 0$	✓ 0
K_{29}	Change in basic rolling moment slope with T_{c_1}'	✓ 0
K_{30}	$\dfrac{\Delta C_{\ell}}{T_{c_2}'}$ at $\delta = 0$	△ -0.003
K_{31}	change in basic rolling moment slope with T_{c_2}'	△ -0.0006
K_{32}	$\dfrac{\Delta C_{\ell}}{\Delta T_{c_3}'}$ at $\delta = 0$	△ -0.003
K_{33}	change in basic rolling moment slope with T_{c_3}'	△ -0.0006
K_{34}	$\dfrac{\Delta C_{\ell}}{\Delta T_{c_4}'}$	✓ 0
K_{35}	change in basic rolling moment slope with T_{c_4}'	✓ 0
K_{36}	$\dfrac{\Delta C_{\ell}}{\Delta \delta A_{L_t}}$	△ +0.00015
K_{37}	$\dfrac{\Delta C_{\ell}}{\Delta \delta A_{R_t}}$	△ -0.00015
K_{38}	$\left(- \dfrac{y_1^2}{b^2} \right)$	✓ 0

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$K_{38.1}\left(-\dfrac{y_2^2}{b^2}\right)$ ✓ -0.0025

$K_{39.1}\ C_{m_{t_0}}$ ✓ .115

$K_{39.2}\ \dfrac{dC_{m_{t_0}}}{d\delta_F}$ ✓ .003 per deg.

$K_{39.3}\ \dfrac{dC_{m_{t_0}}}{d\delta_E}$ ✓ -.02 per deg.

$K_{39.4}\ \dfrac{dC_{m_t}}{d\alpha}$ ✓ -.02 per deg.

$K_{39.5}\ \dfrac{d\,\dfrac{dC_{m_t}}{d\alpha}}{dT'_{c_{2+3}}}$ ✓ +.02

$K_{39.6}\ \dfrac{dC_{n_t}}{d\psi}$ ✓ -.0016

$K_{39.7}\ \dfrac{d\,\dfrac{dC_{n_t}}{d\psi}}{dT'_{c_{2+3}}}$ -.0016

$K_{39.8}\ \dfrac{dC_{n_t}}{d\delta_R}$ ✓ -.0018

$K_{39.9}\ \dfrac{d\,\dfrac{dC_{n_t}}{d\delta_R}}{dT'_{c_{2+3}}}$ -.0008

K_{45}	$\frac{A}{D \times 1728}$	[illegible]
K_{46}	conversion factor from pressure to density of air at constant temp ($T = 520^{\circ}$ R)	✓ .00256 [illegible]
K_{47}		✓ .352
K_{48}	$\frac{j\, C_p'\, t_1}{3600\, (550\, \eta_p)}$	✓ .0015
K_{50}	$\frac{D_p^5}{550}$	✓ 1700 ft^5
K_{51}	$\frac{J}{D_p}$	✓ .533 $\frac{1}{sec}$
K_{52}	D_p^4	✓ 60,000 ft^4
K_{53}	$T'_{c(2-3)}$ (max.)	* 0.5

✓ Data or measurement

✓✓ Estimate from available data - probably close

* Estimate

SET OF CRUISING CONDITIONS FOR MODEL A

CRUISING POWER	1320 BHP (each engine) at 1925 RPM at 10,000 ft.
Gross Weight	63,850 lbs.
C_L	0.6
Velocity	216 MPH
T_c'	.035
α	6.3°
δF	0°
δA_L	0°
δA_R	0°
δR	0°
δE	-2°
γ	0°

LIST OF MISSING FUNCTIONS

f_a, f_b, f_c, f_d, f_e – these terms are for the ground run only

f_{38} thru f_{54} – these functions describe the control surface hinge moment moduli and have not been determined as yet

$$\left.\begin{matrix} f_{56} \\ f_{57} \\ f_{58} \\ f_{59} \\ f_{60} \\ f_{61} \end{matrix}\right\}$$ – these functions describe the engine performance and will be available for the type engine used on the airplane "A" in the near future.

LIST OF MISSING CONSTANTS

K_{38}

K_{39}

K_{40} — these constants involve the control surface hinge moment moduli and are not determined.

K_{41}

K_{42}

K_{43}

LIST OF DELETED FUNCTIONS

f_{22}

f_{31}

f_{33}

f_{35}

f_{36}

f_{37}

$f_{37.1}$

LIST OF DELETED CONSTANTS

K_{24}

K_{26}

$K_{26.1}$

The following drawing numbers of curves for Model A plane are listed for reference. The original graphs are filed in the print department and copies may be obtained as required.

Function Number	Drawing Numbers
$f_1(\alpha, \delta F, T'_{c_{2+3}})$	B - 38000-G B - 38001-G B - 38002-G
$f_2(\delta)$	A - 38003-G
$f_3(\delta E)$	A - 38004-G
$f_4(\alpha, m_n)$	A - 38005-G
$f_5(\alpha, \delta F)$	A - 38006-G-1
$f_6(\delta)$	A - 38007-G
$f_7(\delta R, \delta)$	B - 38008-G
$f_8(\alpha, \delta E)$	B - 38009-G
$f_9(\alpha, m_n)$	A - 38010-G
$f_{10}(\delta, T'_{c_{2+3}})$	B - 38011-G
$f_{11}(\delta R)$	A - 38012-G
$f_{12}(\alpha, \delta E, \delta F, T'_{c_{2+3}})$	A - 38039-G A - 38040-G A - 38041-G A - 38042-G A - 38043-G A - 38044-G A - 38045-G
$f_{13}(\alpha, T'_{c_{2-3}})$	A - 38046-G
$f_{14}(\delta, \alpha)$	A - 38047-G

$f_{15}(\delta R, \gamma)$ .... B - 38048-G

$f_{16}(\alpha, m, n)$ .... A - 38049-G

$f_{17}(h)$ .... A - 38050-G

$f_{18}(\gamma, \delta F, \alpha)$ .... A - 38051-G
A - 38052-G

$f_{19}(\gamma, \delta R, T'_{c_{2+3}})$ .... A - 38053-G

$f_{19.1}(T'_{c_2} - T'_{c_3})$ .... A - 38054-G

$f_{20}(\delta A_L, \alpha)$ .... B - 38055-G

$f_{21}(\delta A_R, \alpha)$ .... B - 38056-G

$f_{23}(\gamma, \delta F, \alpha)$ .... A - 38057-G
A - 38058-G

$f_{24}(\alpha, \delta A_L)$ .... A - 38059-G

$f_{25}(\alpha, \delta A_R)$ .... A - 38060-G

$f_{26}(\delta R)$ .... B - 38061-G

$f_{27}(T'_{c_{2+3}})$ .... A - 38062-G

$f_{28}(T'_{c_{2+3}})$ .... A - 38063-G

$f_{29}(\alpha, \delta F)$ .... A - 38064-G

$f_{30}(\alpha, \delta F)$ .... A - 38065-G

$f_{32}(\alpha, SF)$	A - 38066-G
$f_{34}(\alpha, SF)$	A - 38067-G
$f_{55}(I.A.S, h)$	A - 38068-G
$f_{60.1}(P_2, P_1)$ and $f_{60.2}(P_4, P_3)$	A - 38069-G
$f_{62}(\beta, J)$	B - 38070-G
$f_{63}(\beta, J)$	A - 38071-G
$f_{64}(h)$	B - 38072-G
$f_{65}(h)$	A - 38073-G
$f_{65.1}(h)$	A - 38074-G
$f_{66}(h)$	A - 38075-G

Prepared by S.H. Dandel

Approved by Jay W. Fenster

SD/hs/mgl

6345
Report No. R-102

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: July 25, 1946

Subject: Discussion of Functions in Aircraft Equations of R-64-1, and R-98, by Aerodynamics Group.

Tables: I - II

Written by: Harris Fahnestock

Discussion: An analysis has been made of the functions appearing in the aircraft equations of Reports Nos. R-64 and R-98, to obtain an estimate of the storage space and interpolation time necessary for an adequate representation of the variable coefficients in these equations, and to point out the significance of some of the functions as follows:

1 - Range and accuracy of the functions

2 - Functions for which data is at present somewhat meager but will at some time be more complete

3 - Functions for which more data will be supplied for the airplane now under study

4 - Relative importance of certain functions for this particular airplane and for airplanes in general

5 - Required accuracy of representation or interpolation

Functions 1 through 34, which appear in the equations of motion, have been studied in detail and the estimates for these are reasonably accurate though still subject to revision. Functions 35 through 54, which are involved in the hinge moment equations are not yet as well established and the storage required for these has been estimated to a lesser degree of accuracy. It will be noted that the number of variables involved in some of these latter functions has been reduced from the form in which they appear in R-64, Revision 1, to what they will be in a forthcoming revision 2. Rough estimates have been made for Functions 55 through 66, describing engines, instruments and miscellaneous effects. No estimates are yet available for f_a through f_e which are functions of 2 or 3 variables in the ground terms.

Included herein is a drawing list of all functions, some of which have been recently revised, and all engineers are urged to examine their files for obsolete prints.

In the tables and discussion which follow, each function has been assigned a number of intervals for linear interpolation along each variable sufficient to specify the value of the function to the required accuracy for all points. In some cases where parabolic interpolation is rather obviously indicated, it has been suggested in the detailed remarks on the function but not in the tabular summaries. This does not imply that linear interpolation must be used for any functions but serves as a guide, consistent throughout, as to how closely the given curves must be followed in the method of interpolation used. In general, any method other than linear will require the storage of fewer points and more computation in making the interpolation.

The limited range of the variables in each function is given as the range for which a varying value of that function must be computed. It must be realized that the values of the variables which have been determined elsewhere in the computer may be outside their significant value for a particular function and, if so, some reasonable value of the function, such as zero, a constant, or its maximum value, must be fed out by the interpolator. It may be possible to devise means by which this can be done. If it is not feasible or desirable, the limited range of the variables will have to be extended for each function to include the maximum range of that variable appearing anywhere in the computer, and additional storage and interpolation provided accordingly. In this report the number of intervals is stated to include only the limited range of the variable for which it demands significant and varying values of the function. When a function is symmetrical about an axis, it is assumed that the computer can interpolate for either positive or negative values, and function storage will be required for only one-half of the total range. Examples of this are $f_{30} - f_{31}$, $f_{34} - f_{35}$.

Following a detailed discussion of many of the functions, the required storage is tabulated as follows:

<u>Table I - Functions in Equations of Motion</u> - Opposite each function number in the first column is given the number of points to be stored for it in a column appropriate to the number of variables in that function. The totals show the amount of storage necessary for all functions of different numbers of variables and also the average number of points per function for functions of different numbers of variables. The total number of points necessary for the functions in the equations of motion is approximately 4000.

<u>Tables II, III</u> - give the same for the hinge moments and for the engine, instrument and miscellaneous functions. The total storage required for I, II, and III, together is 6300 points.

<u>Table IV</u> - shows the relative interpolation time required for the groups of functions in I, II, and III, and for all the functions of various numbers of variables. The time for one linear interpolation in a single

variable is taken as 1 and the relative interpolation time for functions of 1, 2, 3, and 4 variables is in the ratio 1, 3, 7, 15.

In the above-mentioned tables, the largest permissible increments of each variable have been used in each function. For purposes of program simplification, it may be desirable to use the smallest reasonable number of different increments of aparticular variable. The cost in storage of making increments of a variable more consistent depends not only on the number of points already stored for a function in which the variable appears, but also on the number of variables whose increments it is desired to change which appear in the function. There are possible combinations too numerous for evaluation.

Table V - lists the cost in storage of possible reductions in the number of increments of 6 of the variables in the equations of motion on the assumption that no single reduction should be made which of itself adds over 150 points to the total storage. This has not included the hinge moment functions.

Tables VI, VII - are a detailed breakdown of the summaries in Tables I, II, and show the variables in each function, their total and limited range, the required intervals for each variable, their increments and the storage required for each function.

Detailed Discussion of Functions:

$f_1(\alpha, \delta F, T'_{c_{2+3}})$ is the largest term in C_Z, the lift coefficient measured along body axes. It will be represented for 4 values of flap angle, δF, and 6 values of thrust coefficient $T'_{c_{2+3}}$.

Along α it may be adequately represented by 20 linear intervals. It is important that $C_{Z_{max}}$ be rather closely given. Most of the curves are near enough straight lines to be represented as such. The stall angle, α_s, corresponding to $C_{Z_{max}}$ will be continuously computed. A straight line representation in one interval can be carried to some point α'_s, either $\alpha'_s = (\alpha_s - \text{constant})$ or $\alpha'_s = \alpha_s - f(\delta F, T'_{c_{2+3}})$.

Beyond this, we must use a curve, either

$$C_Z = C_{Z_{\alpha'_s}} + f(\alpha) \quad \text{or} \quad C_Z = C_{Z_{\alpha'_s}} + f(\alpha, \delta F, T'_{c_{2+3}}).$$

Beyond α_s the value C_Z is not critical and will probably be shown as a drop off to some value of α and a constant thereafter. The above alternates are open for discussion. The summary of storage assumes 20 linear intervals in α. Data will be supplied for $\delta F = 0°, 15°, 30°, 40°$.

$f_2(\delta)$ is the effect of yaw angle δ on the lift coefficient C_Z, and is a factor by which f_1 is multiplied. It will in the future be measured to $\pm 30^\circ$ and estimated to $\pm 40^\circ$. It is symmetrical about $\delta = 0$. Between 30° and 40° it may be a constant or a continuation of the curve. Being a function of only 1 variable, it is probably cheaper to use additional points than to program a constant for $\delta > 30^\circ$. The summary shows intervals for one side only.

$f_3(\delta E)$ is the effect of elevator angle on C_Z. Use linear interpolation with 5 intervals from -30° to $+20^\circ$.

$f_4(\alpha, m_n)$ gives the effect of Mach Number on C_Z. Mach Number is the ratio of airplane velocity to the velocity of sound. The following general remarks apply also to the other Mach Number functions f_9 and f_{16}. The curves supplied do not represent data for this airplane but are included to show the general form of the curves. Obviously the faster the airplane, the more important they become. Although they are not important for this airplane except in a dive, we must be prepared to handle them in the future. The higher the angle of attack the lower the maximum Mach Number it will be possible to attain. The functions as plotted show some impossible or unlikely regions. It is probable that the computation of m_n in equation 60 will avoid ambiguity but consideration should be given to the possibility of further limitation being necessary for transient conditions. For any airplane we may limit α in f_4 from -4° to $+8^\circ$ and m_n from 0 to .8. With present knowledge of m_n we may use 6 linear intervals in α and 8 in m_n. When and if data becomes more accurate it might be desirable to use parabolic interpolation for α with 3 intervals. This probably need not be considered at present. For this airplane the maximum m_n will be approximately .6 at $\alpha \leq 0$, and for $\alpha > 4^\circ$, f_4 will have a negligible value.

$f_5(\alpha, \delta F)$ is the largest term in the drag coefficient C_X measured along body axes. It is shown in Drawing E-38006-G-2 which is quite different from C_D, the drag coefficient along wind axes, Drawing A-38006-G-1. It will be represented for 4 values of flap angle δF, and intervals in α from -4° to $+16^\circ$. It will be necessary as in f_1 to assign some sort of drop off for $\alpha > \alpha_s$, although the shape of the function in the immediate vicinity of α_s is less critical than in f_1. Data will be supplied for $\delta F = 0, 15^\circ, 30^\circ, 45^\circ$.

$f_6(\gamma)$ is the contribution of yaw angle, γ, to the drag coefficient, C_x. It is an important term for which additional data will be supplied to $\pm 40^\circ$. It is symmetrical about $\gamma = 0$. One side can be represented by 8 linear intervals.

$f_7(\delta R, \gamma)$ is the contribution of rudder deflection δR to the drag coefficient C_x for various yaw angles, γ. We will use 4 values of γ either side of $\gamma = 0$ and 6 intervals of δR for the full travel of -30° to $+30^\circ$. Curves are drawn for negative yaw angles. There is a similar family, symmetrical with these, about $\delta R = 0$ for positive yaw angles. Storage is indicated for only negative yaw angles and a program is assumed to take account of positive yaw angles.

$f_8(\delta E, \alpha)$ is the contribution of the elevator angle δE to the drag coefficient C_x for 6 values of angle of attack, α. Curves will be added for $\alpha = 4^\circ, 8^\circ, 16^\circ$. Means must be provided by which the interpolator will supply values such that for $\alpha > 16^\circ$, f_8 is the same as for $\alpha = 16^\circ$ and for $\alpha < 0$, f_8 is the same as for $\alpha = 0$. The total elevator travel δE may be represented by 10 linear or 6 parabolic intervals.

$f_9(\alpha, m_n)$ is the effect of Mach Number on C_x. (See remarks under f_4). It must be included for this airplane. α can be limited from -4° to 8° and use 12 intervals for linear interpolation or 6 for parabolic. The interpolation for m_n may be in 4 intervals provided that m_n is limited from .4 to .8 and that an order is included so that for all α, $f_9 = 0$ when $m_n < .4$. Otherwise storage for m_n must be greatly increased.

$f_{10}(\gamma, T'_{c_{2+3}})$ is the main term in the side force coefficient C_y and is ~~shown in a recent~~ revision, Drawing B-38011-G-1, for 6 values of $T'_{c_{2+3}}$ between which linear interpolation may be used. Note that the curves are not symmetrical about $\gamma = 0$. Twelve linear intervals will be used from $\gamma = -30^\circ$ to $\gamma = +30^\circ$ and either program the value of f_{10} at $\gamma = \pm 40^\circ$ to be the same as $\gamma = \pm 30^\circ$ or extrapolate the data and add additional points.

$\underline{f_{11}(\delta R)}$ is the effect of rudder angle δR on the side force coefficient C_y. It is symmetrical about $\delta R = 0$, the limits of δR being $\pm 30^\circ$. It is represented on one side by 5 intervals.

$\underline{f_{12}(\alpha, \delta E, \delta F, T'_{c_{2+3}})}$ is the most important term in the pitching moment coefficient, C_m. It will be represented for 6 flap angles, δF, and for 6 thrust coefficients, $T'_{c_{2+3}}$. α will be specified by 5 intervals for linear interpolation between -4° and $+16^\circ$. Some value must be assigned to f_{12} for $\alpha > 16^\circ$ but the exact best treatment has not been worked out. One possibility is to have f_{12} fall off rapidly beyond $\alpha = 16^\circ$ by adding one more interval to each curve. Conservatively, we should use the full range of elevator, δE from -30° to $+20^\circ$, using 10 intervals for linear interpolation. The possibility of limiting δE from -20° to $+10^\circ$ is under consideration and efforts will continue to try and reduce the present number of 1296 points to be stored. It must be recognized that this is an extremely important function in the behavior of an airplane and too much compromise cannot be tolerated.

$\underline{f_{13}(T'_{c_2} - T'_{c_3})}$ is the effect of differential thrust on the pitching moment coefficient C_m. It is given in Drawing A-38046-6-1 which was formerly $f_{13}(\alpha, T'_{c_2} - T'_{c_3})$, Drawing A-38046-6. The revised f_{13} is now multiplied by $(1 + K_{14}\alpha)$. The limits are $(T'_{c_2} - T'_{c_3})$ from $-.5$ to $+.5$ and it is not symmetrical. Represent by 6 linear intervals.

$\underline{f_{14}(\gamma, \alpha)}$ is the effect of yaw on pitching moment coefficient C_m. The limits of α are -4° to $+16^\circ$ given by 5 linear intervals. γ from -40° to $+40^\circ$ is symmetrical about $\gamma = 0$ and represented by 5 linear intervals on each side.

$\underline{f_{15}(\delta R, \gamma)}$ is the effect of rudder angle, δR, on the pitching moment coefficient C_m for various yaw angles, γ. We will use 4 values of γ either side of $\gamma = 0$ and 6 intervals of δR for its full travel of $\pm 30^\circ$. Curves are drawn for negative yaw angles and will be supplied for $\gamma = 0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ$. There is a similar family,

symmetrical with those about $\delta R = 0$ for positive yaw angles. Storage is indicated for only negative yaw angles and a program is assumed to take account of positive yaw angles.

$f_{16}(\alpha, m_n)$ is the effect of Mach Number on pitching moment C_m. (See remarks under f_4). α can be limited from 0 to 8° requiring 8 intervals for linear interpolation or 4 for parabolic. m_n can be limited from .6 to .8, using 4 linear intervals provided an order is included so that for all α, $f_{16} = 0$ when $m_n \leq .6$ otherwise storage for m_n must be greatly increased. Model A is a slow enough airplane so that f_{16} is negligible.

$f_{17}(h)$ is the ground effect, that is the effect on the pitching moment C_m of proximity to the ground. Its limits are 0 to 120 feet and it may be represented by 3 parabolic or 6 linear intervals.

$f_{18}(\gamma, \delta F, \alpha)$ is the part of the yawing moment coefficient C_n, due to angle of yaw γ, for various flap angles, δF, and angles of attack α. Together with f_{19}, from which it has been somewhat arbitrarily separated to give 2 functions of 3 variables each, f_{18} and f_{19} determine a very important characteristic of the airplane, namely, its stability in yaw, sometimes called directional stability. For this airplane 2 intervals in α will be sufficient though more may be required for other airplanes. It is characteristic of many airplanes that though the slope of the yawing moment curves may be constant over a rather wide range of yaw angles, there are changes in slope, or even reversals in some cases, in a region very close to $\gamma = 0$. This change in slope within $\pm 4^0$ may give rise to characteristics extremely unpopular with pilots so it must be carefully represented. We have a choice of a simple program with a large number of intervals or a more complicated program with less storage. We may use (a) 80 intervals between $\gamma = -40^0$ to $\gamma = +40^0$, or (b), 20 intervals from $\gamma = -40^0$ to $\gamma = +40^0$ plus 8 intervals between $\gamma = -4^0$ and $\gamma = +4^0$. The summary which specifies 348 points for this function assumes the latter and should be increased to 972 if the former 80 intervals are used.

$f_{19}(\gamma, \delta R, T'_{c_{3+3}})$ is the part of the yawing moment coefficient, C_n contributed by rudder angle δR and thrust coefficient $T'_{c_{2+3}}$. It will be necessary to specify 12 intervals for the full range of

$\delta R = \pm 30^\circ$. In the figure for storage in the summary, 5 intervals of $T'_{c_{2+3}}$ are included but it may be possible to reduce this number. γ can be limited to 8 intervals for $\pm 24^\circ$ provided f_{19} is held constant for the remaining -40° to -24° and $+24^\circ$ to $+40^\circ$. More data will be supplied for this function.

$f_{19.1}(T'_{c_2} - T'_{c_3})$ is a correction term to f_{19} due to unsymmetrical engine operation and will use 5 linear intervals from -.5 to +.5.

$f_{20}(\delta A_L, \alpha)$, $f_{21}(\delta A_R, \alpha)$ represent the part of the yawing moment coefficient C_n, produced by the ailerons for various angles of attack. This is an important function which together with other terms determines the amount of rudder which must be used to start or stop a turn. f_{20} and f_{21} are mirror images about $\delta A = 0$, so it should be necessary to store data for only one aileron. If appropriate programming is too cumbersome, storage can be doubled. Five linear intervals will be used for α and 6 for δA, making a storage requirement of 42 or 84 points.

$f_{23}(\gamma, \delta F, \alpha)$ is the rolling moment, C_ℓ, due to yaw and will be given for 3 angles of attack α and 4 flap angles δF. Additional data will be supplied to extend the yaw angle γ to $\pm 40^\circ$ and make use of 20 linear intervals in this range. The function is symmetrical about $\gamma = 0$ so only half of these need be stored if an appropriate program is set up.

$f_{24}(\alpha, \delta A_L)$, $f_{25}(\alpha, \delta A_R)$ are the rolling moment coefficients, C_ℓ, produced by aileron deflection. The data as measured in the tunnel has appeared in drawings A-38059-G and A-38060-G which show certain features without full scale physical significance which must be attributed to inaccuracies in the model. The new drawings A-38059-G-1 and A-38060-G-1 give a better representation of the actual airplane. Five intervals of α and 12 intervals of δA_L will be used for f_{24}. f_{25} for δA_R is symmetrical with f_{24} about $f_{24} = f_{25} = 0$, $\delta A_L = \delta A_R = 0$ and need not be stored separately.

$f_{26}(\delta R)$ is the rolling moment, C_ℓ, due to rudder deflection δR. It is specified by 12 linear intervals for full rudder travel of $\pm 30^\circ$. Symmetrical so half above storage.

$f_{30}(\alpha, \delta F)$, the yawing moment due to rolling velocity C_{n_p} is an important function in the motion of an airplane but cannot now be measured in the wind tunnel. There will probably be data in the future from contemplated wind tunnel set-ups. The curves shown in drawing A-38065-G have been calculated. They have been simplified in the revised drawing A-38065-G-1 to more realistically represent present accuracy. They may become more complicated in the future. We will use 1 interval in δF and 5 in α for the present accuracy.

$f_{32}(\alpha, \delta F)$, the rolling moment due to rolling velocity C_{l_p} merits the same comments as apply to f_{30}. The simplified drawing is A-38064-G-1.

$f_{34}(\alpha, \delta F)$, the rolling moment due to yawing velocity C_{l_r} is also calculated but with slightly greater accuracy than f_{30} and f_{32}. It may also be better known in the future.

Discussion of Hinge Moment Functions :

As pointed out before, the exact treatment of the hinge moment functions has not been as thoroughly worked out as has that of the functions in the equations of motion. It is believed that the present treatment is adequate and representative of what we will end up with. No drawings of these functions have yet been released but the aerodynamics group has typical curves available for inspection. Table VII lists all current functions; deleted functions are referred to in the drawing list.

$f_{38}(\alpha, \delta E, \delta F, T'_{c_{2+3}})$, the most important term, together with f_{39}, in the elevator hinge moment modulus, K_{H_E} has been reduced from a function of 5 variables by adding $f_{38.1}(T'_{c_2} - T'_{c_3})$. We will use 6 of angle of attack, α, 5 of elevator angle δE, 3 of flap angle, δF. $T'_{c_{2+3}}$ must be described from 0 to .5 but 5 intervals do not seem necessary. Three seem sufficient but would require extra testing for regular intervals. We will tentatively assume 3 intervals without specifying the increments.

$\underline{f_{38.1}(T'_{c_2} - T'_{c_3})}$ which is multiplied by $(1 + K_{40.1}\alpha)$ is a correction to f_{38} to take account of unsymmetrical engine operation and will be given 10 intervals from -.5 to + .5.

$\underline{f_{39}(\delta E_t, \delta E)}$, the contribution of the elevator tab δE_t, to elevator hinge moment modulus K_{H_E}, has been reduced from a function of 3 variables by multiplying it by a factor $(1 + K_{40.2}\, T'_{c_{2+3}})$ which will adequately take care of variations caused by thrust coefficient. The change in f_{39} with angle of attack, α, is small enough to be omitted. We will use 8 intervals of tab angle, δE_t, and 5 of elevator angle, δE.

$\underline{f_{40}}$ and $\underline{f_{41}}$ have both been reduced fromfunctions of T'_{c_2} and T'_{c_3} to functions of $T'_{c_{2+3}}$ and require 5 intervals for each.

$\underline{f_{42}(\gamma, \delta R, T'_{c_{2+3}})}$ the most important term, together with f_{43}, in the rudder hinge moment modulus, K_{H_R}, has been reduced from a function of 4 variables in a manner analogous to the treatment of f_{38}. γ may be limited to $\pm 30^\circ$ if the value of f_{42} is held constant from there out to $\pm 40^\circ$ and will be given for 12 intervals in the limited range. The rudder angle δR, will have 12 intervals for its range of $\pm 30^\circ$. $T'_{c_{2+3}}$ as in f_{38} will have 3 intervals. Thisresults in a storage of 676 points which may be reduced if it is possible to program some sort of symmetry which appears in the curves.

$\underline{f_{42.1}(T'_{c_2} - T'_{c_3})}$ is treated similarly to $f_{38.1}$.

$\underline{f_{43}(\delta R_t, \delta R)}$ is treated similarly to f_{39} with additional points to take care of the greater range of δR than δE.

$\underline{f_{44}}$ and $\underline{f_{45}}$ are deleted.

$f_{46}(F'_{c_{3-3}})$ has 5 intervals.

$f_{47}(\delta A_L, \alpha, \delta F)$ is part of the left aileron hinge moment modulus $K_{H_{A_L}}$ and requires 6 intervals in aileron angle δA_L, 6 in angle of attack, α, and 3 in flap angle, δF.

$f_{48}(\delta)$ has been reduced from a function of 2 variables and is now multiplied by δA_L. It is symmetrical about $\delta = 0$ and requires 8 intervals on each side.

f_{49} is deleted.

$f_{50}(\delta A_{L_t}, \delta A_L)$ is the part of $K_{H_{A_L}}$ due to left aileron tab δA_{L_t}. It is specified by 8 intervals in δA_{L_t} and 6 in δA_L.

f_{51}, f_{52}, f_{53}(deleted), and f_{54} are analogous to f_{47} to f_{50}. These functions for the right aileron are symmetrical with the left and it is assumed that a program can be worked out similar to f_{24} and f_{25}. No storage is tabulated.

TABLE I

STORAGE FOR EQUATIONS OF MOTION

Function Number	NUMBER OF POINTS STORED 1 Variable	2 Variable	3 Variable	4 Variable
1			504	
2	5			
3	6			
4		33		
5		34		
6	9			
7		35		
8		66		
9		65		
10		78		
11	7			
12				1584
13	7			
14		36		
15		35		
16		45		
17	7			
18			348	
19			703	
19.1	6			
20		43		
23			133	
24		78		
26	7			
30		14		
32		14		
34		14		
TOTAL	54	669	1686	1584
Per FCN.	7	50	400	1600

TOTAL POINTS 3993

TABLE 11

STORAGE FOR HINGE MOMENTS

Function Number	NUMBER OF POINTS STORED			
	1 Variable	2 Variable	3 Variable	4 Variable
38				672
38.1	11			
39		54		
40	6			
41	6			
42			676	
42.1	11			
43		63		
46	6			
47			196	
48	9			
50		63		
TOTAL	49	180	872	672

TOTAL POINTS 1773

TABLE III

STORAGE FOR ENGINE, INSTRUMENT AND MISCELLANEOUS FUNCTIONS

Function Number	NUMBER OF POINTS STORED	
	1 Variable	2 Variables
55		45
56		50
57		100
58		30
59		100
60	21	
60.1	4	
61	11	
62		88
63		88
64	3	
65	11	
65.1	6	
66	11	
TOTAL	67	501

TOTAL POINTS 568

Only one engine need be stored.

TABLE IV

INTERPOLATION TIME

Equations of	NUMBER OF FCNS OF 1 TO 4 VARIABLES				Relative Interpolation Time
	1 var.	2 var.	3 var.	4 var.	
Motion	8	16	4	1	99
Hinge Moments	7	4	3	1	55
4 Engines	12	24			84
Insts. and Misc.	4	1			7
TOTAL	31	45	7	2	
Relative Interpolation Time	31	135	49	30	245

TABLE V

REDUCTION OF INCREMENTS OF VARIABLES

Variable	Increments of Variable		Additional Storage
	Now	Possible	
δ_E	5° 10°	5°	7
δ_R	5° 10°	5°	50
δ_A	5° 10°	5°	36
δ_F	5° 45°	15°	42
α	1° 2° 4° 10°	1° 4° 10°	54
γ	1° 4° 5° 6° 8° 10°	1° 5° 6° 10°	-6
		1° 5° 10°	150

TABLE VI

STORAGE FOR EQUATIONS OF MOTION

Equation	Function	Variable	Range				Linear		
			Total		Limited		Intervals	Increments	Points
26	1	α	-20	+40	-4	+16	20	1°	504
		δ_F	0	60	0	45	3	15°	
		$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	
25	2	γ	-40	+40	-40	+40	4	10°	[illegible]
26	3	δ_E	-30	+20	-30	+20	5	10°	[illegible]
26	4	α	-20	+40	-4	+8	6	2°	63
		m_n	0	.8	0	.8	8		
27	5	α	-20	+40	-4	+16	20	1°	84
		δ_F	0	60	0	45	3	15°	
27	6	γ	-40	+40	-40	+40	8	5°	9
27	7	δ_E	-30	+30	-30	+30	6	10°	55
		γ	-40	+40			4	10°	
27	8	δ_E	-30	+20	-30	+20	10	5°	66
		α	-20	+40	-4	+16	5	4°	
27	9	α	-20	+40	-4	+8	12	1°	65
		m_n	0	.8	.4	.8	4		
28	10	γ	-40	+40	-30	+30	12	5°	73
		$T'_{c_{2+3}}$	0	.5	0	.5	6	.1	

(Continued)

TABLE VI (Continued)

Storage for Equations of Motion

Equation	Functions	Variable	Range Total		Range Limited		Linear Intervals	Increments	Points
28	11	δ_E	-30	+30	-30	+30	6	5°	7
29	12	α	-20	+40	-4	+16	5	4°	1684
		δ_E	-30	+20	-30	+20	10	5°	
		δ_F	0	60	0	45	3	15°	
		$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	
29	13	$T'_{c_2}-T'_{c_3}$	-.5	+.5	-.5	+.5	6	7	7
29	14	γ	-40	+40	-40	+40	5	8°	36
		α	-20	+40	-4	+16	5	4°	
29	15	δ_R	-30	+30	-30	+30	6	10°	35
		γ	-40	+40	-40	+40	4	10°	
29	16	α	-20	+40	0	8	8	1°	45
		m_n	0	.8	.6	.8	4		
29	17		0	120	0	120	6		7
30	18	γ	-40	+40	-40	+40	28	$1^\circ, 4^\circ$	349
		δ_F	0	60	0	45	3	15°	
		α	-20	+40	-4	+16	2	10°	
30	19	γ	-40	+40	-24	+24	8	6°	70
		δ_R	-30	+30	-30	+30	12	5°	
		$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	

(Continued)

TABLE [illegible] (Continued)

Storage for Equations of Motion

Equation	Function	Variable	Range Total		Range Limited		Linear Intervals	Increments	Points
30	19.1	$T'_{c_2} - T'_{c_3}$	-.5	+.5	-.5	+.5	5		5
30	20	δ_{A_L}	-30	+30	-30	+30	6	10°	42
		α	-20	+40	-4	+16	5	4°	
30	21	δ_{A_R}	Similar to f_{20}						
		α	No Storage						
31	23	γ	-40	+40	-40	+40	10	4°	112
		δ_F	0	60	0	45	3	15°	
		α	-20	+40	-4	+16	2	10°	
31	24	α	-20	+40	-4	+16	5	4°	76
		δ_{A_L}	-30	+30	-30	+30	12	5°	
31	25	α	Similar to f_{24}						
		δ_{A_R}	No Storage						
31	26	δ_R	-30	+30	-30	+30	6	5°	7
35	30	α	-20	+40	-4	+20	6	4°	14
		δ_F	0	60	0	45	1	45°	
36	32	α	-20	+40	-4	+20	6	4°	14
		δ_F	0	60	0	45	1	45°	
37	34	α	-20	+40	-4	+20	6	4°	14
		δ_F	0	60	0	45	1	45°	

Total Points 3993

TABLE VII

STORAGE FOR HINGE MOMENTS

Equation	Function	Variable	Range Total		Range Limited		Linear Intervals	Increments	Points
40	38	α	-20	+40	-4	20	6	4°	576
		δ_F	0	60	0	45°	3	15°	
		δ_E	-30	+20	-30	+20	5	10°	
		$T'_{c_{2+3}}$	0	.5	0	.5	5	?	
40	38.1	$T'_{c_2} - T'_{c_3}$	-.5	+.5	-.5	+.5	10	.1	11
40	39	δ_{E_t}	-20	+20	-20	+20	8	5°	54
		δ_E	-30	+20	-30	+20	5	10°	
41	40	$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	6
43	41	$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	6
43	43	β	-40	+40	-30	+30	12	5°	378
		δ_R	-30	+30	-30	+30	12	5°	
		$T'_{c_{2+3}}$	0	.5	0	.5	5	?	
43	43.1	$T'_{c_2} - T'_{c_3}$	-.5	+.5	-.5	+.5	10	.1	11
	43	δ_{E_t}	-20	+20	-20	+20	8	5°	68
		δ_E	-30	+30	-30	+30	6	10°	
44	46	$T'_{c_{2+3}}$	0	.5	0	.5	5	.1	6
45	47	δ_{A_3}	-30	+30	-30	+30	6	10°	196
		α	-20	+40	-4	+20	6	4°	
		δ_F	0	60	0	45	3	15°	

(Continued)

TABLE VII (Continued)

Storage for Hinge Moments

Equation	Function	Variable	Range Total		Range Limited		Linear Intervals	Increments	Points
	48	γ	-40	+40	-40	+40	8	5°	9
	50	$\delta_{A_{L_t}}$	-20	+20	-20	+20	8	5°	63
		δ_{A_L}	-30	+30	-30	+30	6	10°	
46	51	δ_{A_R}	)						
		α	)						
		δ_F	)	Same as					
			)	Equation 45					
	53	γ	)	No additional					
			)	Storage					
	54	$\delta_{A_{R_t}}$	)						
		δ_{A_R}	)						

Total Points 1773

FUNCTION DRAWING LIST JULY 11, 1946

FUNCTION	OBSOLETE DRAWING	CURRENT DRAWING
1		B-38000-G to B-38002-G
2		A-38003-G
3		A-38004-G
4		A-38005-G
5	A-38006-G-1	A-38006-G-2
6		A-38007-G
7	B-38008-G	B-38008-G-1
8		B-38009-G
9		A-38010-G
10	B-38011-G	B-38011-G-1
11		A-38012-G
12		A-38039-G to A-38045-G
13	A-38046-G	A-38046-G-1
14	A-38047-G	A-38047-G-1
15		B-38048-G
16		A-38049-G
17		A-38050-G
18		A-38051-G to A-38052-G
19		A-38053-G
19.1		A-38054-G
20		B-38055-G
21		B-38056-G
22		Deleted
23		A-38057-G to A-38058-G
24	A-38059-G	A-38059-G-1
25	A-38060-G	A-38060-G-1
26		B-38061-G
27	A-38062-G	Deleted
28	A-38063-G	Deleted
29	A-38064-G	Deleted
30	A-38065-G	A-38065-G-1
31		Deleted
32	A-38066-G	A-38066-G-1
33		Deleted
34	A-38067-G	A-38067-G-1
35		Deleted
36		Deleted
37		Deleted
44		Deleted
45		Deleted
48		Deleted
53		Deleted
60		A-38068-G
60.1		A-38069-G
60.2		A-38069-G
62		B-38070-G
63		A-38071-G
64		B-38072-G
65		A-38073-G
65.1		A-38074-G
66		A-38075-G

Written by: Harry Fahnestock

Approved by: J. W. Forrester
by RRE

HF:hes

DIC 6345

CONFERENCE NOTES C-15

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date: October 9, 1946

Place: Conference Room Servomechanisms Laboratory

Subject: Coding of Aircraft Flight Equations

1. The Problem Studied.

A possible method of solution of the ASCA problem has been programmed in terms of the code described below in order to get an estimate of the amount of storage required, the number of operations of each type, the time required to write out the program and the time required by the computer to complete a solution. For this trial, modifications were made to the equations of 6345 R-64 as follows:

Ground terms were omitted with the realization that their inclusion would increase the amount of program storage but not the computation time. Engine equations were omitted as being at the present insufficiently specified, (it is estimated that they will add 10% to the solution time). Algebraic transformations were made in the flight equations to better adapt them to digital computation rather than analogy for which they were originally written.

The following mathematical method was adopted for this trial solution:

Available at the beginning of a computation interval are a measured value of each control position and the computed value of each of the rates and angles at the end of the three previous computations. These rates and angles are then extrapolated for one time interval to their approximate or assumed values for use in the present computation. These extrapolated values and the measured control positions are used to compute the quantities which are integrated to give the true rates and angles.

Numbered storage registers must be specifically assigned in which are held the values of all the quantities necessary in the computation. Dead storage registers are assigned for the constants and the values of each of the functions. Live storage registers are assigned for all necessary variables and partial results. The program is then written in terms of those register numbers without regard to the value of the quantity stored in the register. Thus the program as written is entirely general as regards both time and type of airplane. Based on the 6300 constant values required by 6345 R-103, which was estimated to be 3/4 of the required storage, register numbers from 0001 to 8192, the closest appropriate power of 2, were allocated.

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II. Operation Code Chosen

The programming was carried out under the assumption of a computer capable of performing the operations listed in the table below. The order used is a binary number consisting of 4 parts:

D	A	B	C

The "D" section contains the code for the desired operation. The A, B, C sections are usually register numbers but may be used for other purposes. Where the letter alone is given, it means the number of the register. When parentheses are given around the letter, it means the number or order stored in that register. The machine is presumed to use binary code but all orders were written as decimal numbers for convenience.

It is further assumed that 0000 in the C position stands for use of the accumulator in the computer and means to retain the result and add it to the next result. The negative multiplication and addition orders are given to provide for accumulation of products or sums with varying sign.

The first 3 operations provide the basic arithmetical processes. The next 5 are largely for purposes of convenience while the last 2 allow the machine to perform alternate series of operations, to look up information in tables and to perform other more complicated processes.

	Code Symbol	Operation	Meaning
Basic	a	addition	(A) + (B) = (C)
	s	subtraction	(A) − (B) = (C)
	m	multiplication	(A) x (B) = (C)
Convenient	n	negative multiply	(A) x (B) = −(C)
	j	negative addition	(A) + (B) = −(C)
	t	transfer	(A) to B (A+1) to B+1 for C times
	e	shift positive	Put (A) x 2^{C} in B
	f	shift negative	Put (A) x 2^{-C} in B
	p	sub-program	Take next order from A continue in this sequence for B times, then return to C.
	c	compare	If (A) < (B) take next order from C If (A) ≥ (B) continue in previous sequence.

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Code Symbol	Operation	Meaning
1	Implicit Program (extraction order)	Transfer digits from (A) to (B), the first part of C determines starting place in (A), the second part the starting place in (B), the third part the number of digits to be transferred.

Further Assumptions

1. Storage.

It is assumed that any word may be removed from storage at any time. It is not necessary to order erasing. This leads to such requirements as taking 2 numbers from EST and storing the result on a 3rd line of the same tube. This would require 4 sweeps of the tube including erasing. Since there are only 2 word lengths per operation, this cannot keep up.

2. Negative numbers may be handled. It is not necessary to say how but it will probably be by the use of complements.

3. Division, square rooting, generation of logarithms, trigonometric functions, etc., will not be built in but will be programmed using iterative processes, stored tables or series.

III. Example

An example using this code was given. The example chosen was linear interpolation in 1 variable - an operation of frequent occurrence in the ASCA problem. The example is written for interpolation in f_3 (SE) although the sample curve shown bears little resemblance to the actual function.

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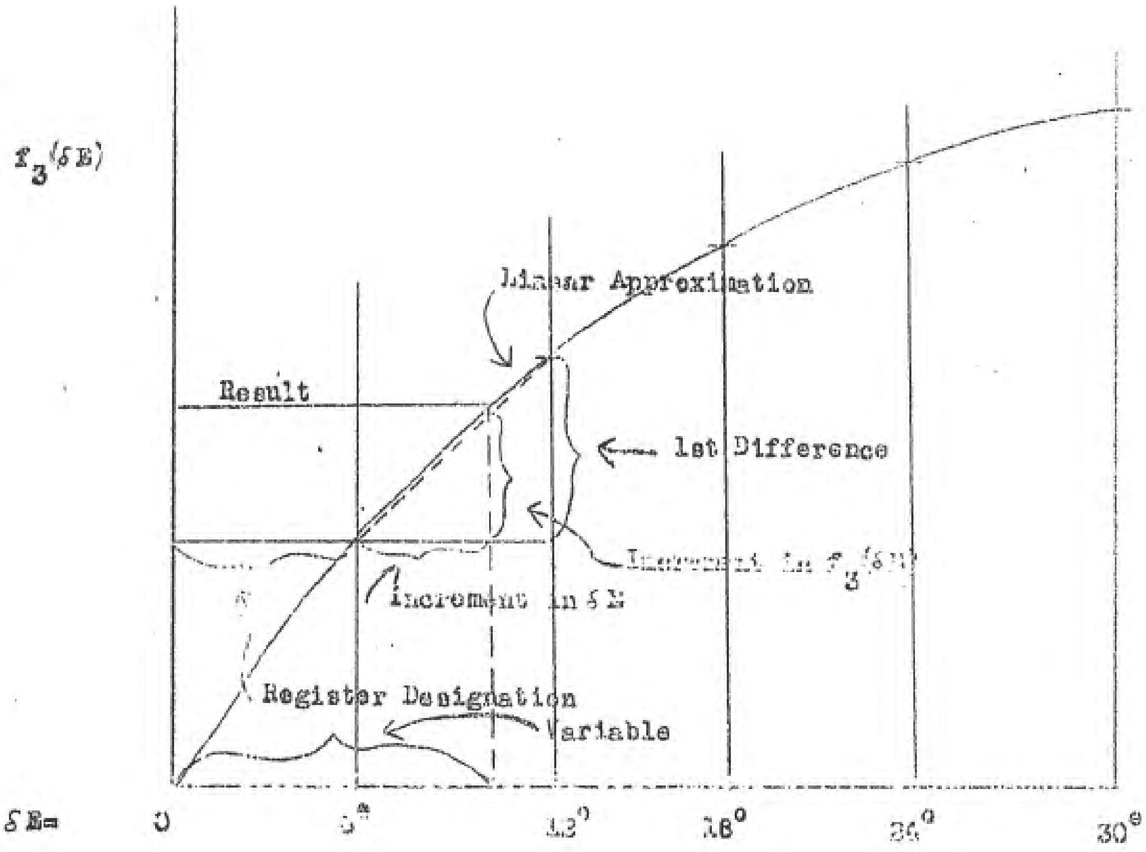

Register No.

	1746	1747	1748	1749	1750	1751
$\delta E \times \frac{1}{6}$	0	1	2	3	4	5
$\delta E \times \frac{1}{6} + 1746$	1746	1747	1748	1749	1750	1751

The following information is also stored:

Ratio $\frac{1}{6}$ is stored in register	1752
Starting register No. stored in reg.	1753
δE is stored in register	7801
The sub-program is stored in reg.	901ff
The partial results may be stored in	7848
These registers are	7894
normally empty	7895
or	7896

This information is sufficient for performing interpolation in the function.

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A program was then written for this interpolation as an example using the previously mentioned code. The following form was used:

Order No.	D	A	B	C	
0228	m	7801	1752	7848	First normalizing step Multiplies by ratio stored in 1752 (in this case $\frac{1}{6}$)
0229	a	7848	1753	7894	Second normalizing step. Add zero register position. (Register number holding the value of the function for which the argument is zero - here 1746) Result is in register 7894.
0230	p	0901	0005	0321	Sub-program order. This order is not necessary for the interpolation but allows using a single set of sub-program interpolation orders for a number of different interpolations. The order says to take the next 5 orders from the sequence beginning with 0901 and then to return to order No. 0231.
0231	t	7894	7848	0001	This order transfers the result of the interpolation from register 7894 to register 7848 so that 7894 may be available for other interpolations.
0901	i	7894	0902	1204	This is the first order in the sub-program. The desired register position holding the value of function at the beginning of the interval in question has been computed and lies in register 7894. The first 4 digits (the register number) are transferred to the A section of order 0902 by this order. The digits remaining in 7894 are the increment in the argument.
0902	t	blank	7895	0002	The blank has been filled with the desired register number by the previous order. The value of the function in this and the next register are here transferred to registers 7895 and 7896.
0903	s	7896	7895	7896	The first difference is taken and stored in 7896 since the second value of the function is no longer needed.
0904	m	7896	7894	7896	The difference is multiplied by the increment in the argument. The resulting increment in the function is stored in 7896 since the first difference is no longer needed.

Order No.	D	A	B	C	
0905	a	7896	7895	7894	The increment in the function is added to the value of the function at the beginning of the interval. The result is stored in 7894. The program control now returns to the main program where the result may be used immediately or transferred to some other storage register.

It will be noted that the sub-program will work for any function. The choice of the function and variable is up to the main program. The sub-program need be written only once and can be used at any time by inserting an order such as No. 0230 in the main program.

The following table shows the number of orders required for each type of interpolation. The table does not include an operation for transferring the result.

No. of Variables	Main Program Orders	Sub-program Orders	Total Operations	No. of Times Interpolation Performed in ASCA Solution
1	3	5	9	27
2	9	13	24	22
3	15	29	46	7
4	23	61	92	2

The ASCA solution was carried out using this code and required the following numbers of operations:

Total	1702
Main Program	841
Sub-Program	861
For the Interpolations	1327
For all other operations	375

The number of operations of each kind were:

Multiplications	m	492
Neg. Mult.	n	16
Additions	a	393
Subtractions	s	192
Transfers	t	332
Subprograms	p	68
Shift	e	83
Comparisons	c	9
Implicit Orders	i	115

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The times required for a solution of the problem for different systems are given below. These times are for the aircraft and hinge moment equations and should probably be increased about 10% for a complete solution.

For a serial computer allowing 100 μs per operation	170,000 μs 6 solutions per second
For a serial computer with built in high speed interpolation	48,000 μs 20 solutions per second
For a parallel computer allowing 100 μs for mult. 10 μs for others	63,000 μs 16 solutions per second
For a higher speed parallel computer allowing 40 μs for mult. 10 μs for others	32,000 μs 30 solutions per second

Mention was made of a study of scale factors now being carried out by Mr. Fahnestock.

Harris Fahnestock

Harris Fahnestock

Robert R. Everett

Robert Everett

RRE:HF
mla

MEMORANDUM NO. M-65

TO: 6345 Engineers

FROM: H. Fahnestock

SUBJECT: Solution of Simplified ASCA on WW-I.

REFERENCE: 6345 Reports: Nos. R-64-1; R-98; R-103.
Notebooks: 2HF4-12; 2HF4-14; 3HF4-15.

DATE: March 31, 1947

It has been suggested that the WHIRLWIND I computer might be used to solve a portion of the Aircraft Stability and Control Analyzer problem described in the referenced reports. WHIRLWIND I will differ from the final computer primarily in the reduced amount of storage available for data describing the aircraft, for the program to be used in solving its equations of motion, and in the number of digits carried in the computation. The latter does not appear to be a serious limitation. It is proposed to restrict the solution to certain parts of the aircraft motion but not to compromise the accuracy of that part of the solution which is computed except as to the lesser number of digits mentioned above. Such use of WHIRLWIND I will serve to demonstrate the suitability of the final computer as a means of solving in real time for the motion and feel of an aircraft by digital computation based on Wind Tunnel data. It will be possible to study the effect of varying length of computation interval both on accuracy of solution and pilot's illusion of realism.

It will be assumed that the angles of roll and yaw will be kept zero at all times as they might by an automatic pilot. A solution will be obtained for the longitudinal motion including pertinent instrument readings, and elevator hinge moments will be fed back to the control column. Take-off and landing will not be handled; stall will be indicated by appropriate instrument readings and control forces. There are three possibilities for treating flaps, one of which will be chosen after a determination of the actual amount of storage to be incorporated in WW-I:

a) Flaps always retracted

b) Flaps either up or down to a predetermined angle

c) Flaps up or down to a predetermined angle with a smooth (but numerically meaningless) change of trim between the two positions.

With the storage capacity contemplated for WW-I, (a) can certainly be handled and it is likely that the solution can be as elegant as (c).

Complete restrictive assumptions made in the above estimate

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include the following:

Motion limited to XZ plane.

Flap positions limited to 2.

Mass and center of gravity fixed.

Maximum altitude limited to 10,000 feet.

Effect of Mach number omitted.

Landing gear up; cowl flaps and bomb doors closed.

Single unsupercharged engine.

Fixed pitch propeller.

Propeller rotation effects omitted.

Structural deflection terms omitted.

Harris Fahnestock

H. Fahnestock

HF:has

c.c. Prof. J. C. Hunsaker
Prof. J. R. Markham
Prof. J. Bicknell
Dr. G. S. Brown
Prof. O. C. Koppen

6345
Report 94

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Mass.

Date of Report: February 12, 1946

Subject: Some Psychiatric Observations on Cockpit Design

Prepared by: Richmond Holder, M. D.

Reference: "Factors in the Design of Air Transport Planes" by Ross McFarland, and personal observations and conversations with pilots.

Comments by Mr. Forrester: Attached is an outline prepared by Dr. Holder of the Massachusetts General Hospital on factors affecting cockpit design. Dr. Holder has not attempted to write a completed report but to merely indicate certain factors which will need to be studied and discussed at a later date. They act as a preliminary guide to the formulation of a research program in cockpit design.

Jay W. Forrester

CONTENTS

I PROPER SEATING OF PILOT

1. Observations

Seating must be analyzed from two points of view:

a. The subjective comfort of the pilot
b. The physiological effects on the pilot

These two viewpoints are not necessarily interdependent. What is subjectively comfortable for one hour may be very uncomfortable for ten hours. It also may be very detrimental to the pilot from the physiological viewpoint. To illustrate, Dr. M. N. Smith-Petersen of the M. G. H., an experienced orthopedic surgeon, has found that most pilot seats place the spine in a very vulnerable position. Over a long period such a position enhances the risk of sustaining minimal fractures which will ultimately lead to disabling symptoms.

The pilots often feel that the seats are improperly built for what the pilots have to do, i.e., from a functional standpoint. They also feel that certain features might profitably be added such as arm rests and more adjustability of each seat to suit the person using it.

2. Conclusions

Since pilot fatigue (both subjective and physiological) is very closely related to proper seat design and since in the long run there is danger of permanently injuring the pilots by improper seating, it would seem highly desirable to have orthopedic consultants working on the problem along with psychiatrists. In particular avoidance of a seat promoting flexion of the dorsal and lumbar spine and extension of the cervical spine is to be desired. From the subjective point of view the pilot must be able to change position often which, of course, has a very beneficial physiological effect as well by promoting circulatory changes and avoiding poor tissue oxygenation. As a corollary to this many pilots feel that one of the most important parts of an aeroplane's flight characteristics is an ability to stay on trim so that they can stretch their legs without fear of accident.

With more and more equipment being added to the pilot's parachute such as life rafts, etc., it becomes especially important to take such apparatus into account when designing the seat. In one current model the back pack is so bulky that it pushes the pilot forward in his seat. It not only makes him extremely uncomfortable but also makes it inconvenient to operate the controls. Such arrangements must be avoided.

II CONTROL OF COCKPIT TEMPERATURES AND VENTILATION

1. Observations

The psychological and physiological considerations of ventilation are highly important when it is realized that much flying is now being done in extremes of temperature at high altitudes, where the oxygen content of the air is greatly lowered. Besides this the presence of carbon monoxide in the cockpit (the most important source of which is from the exhaust gases) must be carefully controlled. It can produce symptoms ranging from mild headaches to complete loss of consciousness and coma with intermittent convulsion.

To take up the ventilation itself first, it is a well known psychiatric observation that if two rooms have air at the same temperature and purity, but with the air moving in one and still in the other, the room with the moving air may feel bracing and stimulating while the other is subjectively close and oppressive. Besides this body warmth itself is inter-related with ventilation. This would seem to be all obliviated by the fact that pilots wear heated suits and have heaters in their planes but all too often the latter two devices get out of order. This is a common complaint from many pilots.

As far as the CO is concerned its sources which include not only

(a) the exhaust gas from the engine leaking into the cockpit due to the fact that the air inside the cockpit is often at a lower pressure than the air outside -- but also
(b) heating units inside the cabin -- and
(c) heat exchangers --

must all be carefully controlled.

2. Conclusions

As movement of air, proper oxygen content, proper carbon monoxide control, humidity, and temperature all have an important effect on not only the subjective comfort of the pilot but also his psychological and motor efficiency, these items should be considered in detail in the design of the cockpit and aeroplane as a whole. Such things as a mal-directed stream of air may not only be extremely annoying but also detrimental physiologically as in the Martin M-130 where the hot air blown into the cockpit tended to dry the conjunctival secretions of the eye and resulted in very irritated eyelids.

III THE PSYCHIATRIC ASPECTS OF NOISE IN AIRCRAFT

1. Observations

Many studies have been made of the effect of sound on human performance and subjective feelings, especially by the Harvard Psycho-Acoustical Lab. Although it was found that noise levels had a very slight effect (detrimental) upon functions involving motor coordination, reaction time, sensory perceptions, and certain mental functions, nevertheless high levels of noise produced definite subjective feelings of fatigue and irritability upon the pilot. This was in reference to engine noise and other externally caused noises such as aerodynamic and ventilating noise and secondary sources of noise arising from vibration within the cockpit. However, many pilots complain of radiostatic noise as being infinitely worse than the previously mentioned sources. The unexpectedness of noise coming from the radio was said to be especially annoying.

2. Conclusions

Control of noise by stoppage of sound leaks (which tend to offset the value of elaborate acoustical treatment, by filtering out the noise from ventilating and heating systems before admitting air to the cabin, and similar procedures would most probably prove profitable in the long run by diminishing fatigue and augmenting mental performance. Psychological tests at present do not seem to be sensitive enough to prove the latter point but considerable evidence supports it.

IV COCKPIT CONTROL ARRANGEMENT

1. Observations

Cockpit controls from the point of view of the pilot have many drawbacks. These involve such general principles as placing important emergency controls on the right side of the cockpit where they will have to be operated with the left hand (an awkward and time-consuming maneuver in a situation where dexterity and speed are essential) and having controls of one group intermixed with those of another (i.e., the hydraulic pump handle of the TBM-3 is mixed in with the radio controls and very difficult to get at). This problem also involves specific operational worries of the pilot which seem to be common to many airmen. To illustrate this point, one of the most constantly observed indicators in a plane is the fuel tank gauge. The pilots subconsciously are compelled to be constantly rechecking the amount of fuel left. Since very often these gauges are located in an inconvenient place, the pilot's attention is distracted from flying and he is constantly obliged to shift his attention away from the flight controls. Finally some controls are placed in such a position as to actually interfere with flying, i.e., in one of the earlier TBM's the auxiliary compass was placed overhead which made flying in the number 4 Spot of a V-formation extremely difficult.

The previous observations are all on the negative side, but there is also the positive side to be considered. This would include such things as having the entire cockpit layout standardized into main control groups, each one in the same relative position in all planes and each one with an identifying color. This has the obvious advantage of enabling pilots to use different craft interchangeably and also of avoiding costly errors in actual operation by either handling of the wrong controls or wasting time locating the right ones. There have been many accidents involving unintentional operation of switches or controls at vital moments, i.e., originally there was no guard on the master ignition switch of the B-314. During one flight one of the crew members apparently jarred this switch off accidentally. All four engines of the plane stopped in the middle of a transoceanic flight while cruising at 8000 feet and the plane lost over 2000 feet of altitude before the difficulty was discovered.

2. Conclusions.

Since all of the aforementioned things are very distracting to the pilot and promote fatigue, it would seem worthwhile to incorporate some of the following general suggestions into cockpit layout.

a. Use of Shape - specific shapes for specific controls, possibly related to the actual use (i.e., a round wheel for the landing gear control).

b. Use of color - this has long been used for specific controls but it might seem valuable to apply it to

entire groups of controls (i.e., bounding each area of similar controls by a color appropriate to that group. These might be done in fluorescent paint.)

c. Use of Grouping - placing all controls of one group (such as those instruments used for flying proper) in one area.

d. Placing the most frequently observed instruments in the most accessible places with due regard to all the above mentioned factors. This could be determined by careful checking with a large group of pilots.

e. Protection of controls against inadvertent use by either countersinking important switches so that they can not be thrown accidentally or putting guards requiring conscious effort over them.

V PSYCHIATRIC ASPECTS OF SIMULATOR

1. Preparation of Pilot before Flight

   a. Dressing in full equipment including flying suit and parachute and safety equipment. (i.e. life raft, etc.)

   b. Standard comments pre-flight (preferably a minimum of remarks)

2. Proper presentation of the apparatus

   a. The approaches (preferably with complete masking of all machinery and control rooms)

   b. Outside flight conditions (these are important because of their psychological effects on the pilot and their action on the inside of the cockpit - i.e., as in the M-130 where hot dry air irritated the pilot's eyes)

      i. Weather, thunder, lightning
      ii. Speed of air, hail, etc.

All these things will produce an effect on inside conditions of the cockpit i.e., ventilation, vibration, noise, temperature, and oxygen supply with especial regard for such factors as to whether super-charging is being used.

3. Rigid control and constant setting of post-flight evaluation.

   a. Standard form of questionnaire re flight specifications.

   b. Standard form for subjective responses to flight characteristics of the plane.

   c. After the above two are completed, the pilot may be questioned ad lib.

4. Long-range flight conditions.

   a. It is imperative for both psychological and physiological reasons that the pilot stay in the simulator for times comparable with those met in actual operations. These are not only important separately but also as interacting factors, i.e., long continued sitting with its physiological discomfort has a decided effect on the mental outlook of the pilot.

5. Over all control of the program.

   a. It would seem important for each pilot to be held to silence about the testing so that there may be a minimum of preconceived ideas in each subsequent tester.

b. Complete standardization as to time, form and procedure in each test run must be carefully maintained to assure validity of results.

Written by. Richmond Holder, M.D.

6345
Report No. R-100

Restricted
M.I.T. and Navy Circulation

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: March 4, 1945

Written by: James B. Swett

Subject: Method of Cockpit Mounting and Actuating Mechanism.

Drawings:
L-37501
D-37504

References: Computations in 1JBS10-29
6345, Report No. R-99
1AHS15-17
Drawings:
L-37501
D-37504
D-37503
L-37502

Discussion: During the period February 1 to March 1, 1946, methods of mounting and actuating the ASCA cockpit were investigated. Of the various methods discussed, only three seem to warrant mention in this report. The comparative merits and disadvantages of these three methods will be reviewed.

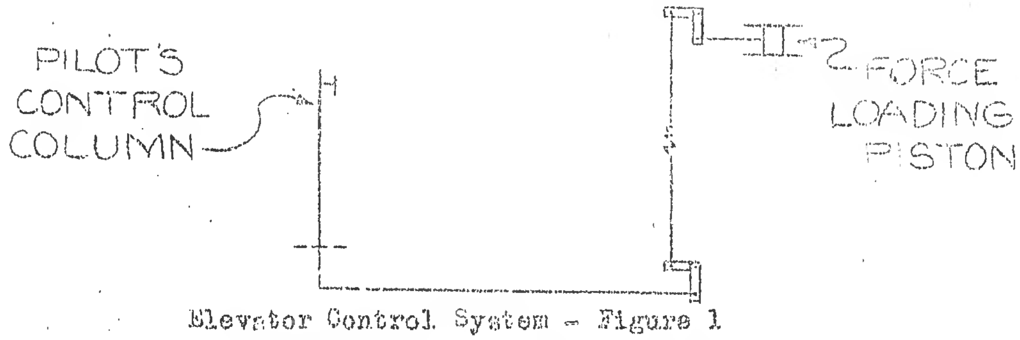
A) - 1. Mounting Cockpit in Gimbals on Top of a Vertical Steel Tube.

This method seemed feasible until it was determined that mounting the cockpit in such a manner resulted in undesirable physical effects on the pilot. In order to duplicate the sensations experienced in a yaw or sideslip, it was proposed to roll the cockpit about an axis below the pilot, provided this might be done by some mechanical means. This method of mounting immediately proved unsatisfactory from the standpoint of "feel". To simulate a sideslip to the right, the cockpit must be initially rolled to the right tending to throw the pilot to the left with respect to the seat. However, if the cockpit is stopped at some degree of this right bank, the pilot has a tendency to fall out the right side of this seat which is the opposite to the desired effect. To avoid such complications it is necessary to mount the cockpit from some point above the cockpit. When mounted to move about an axis above the pilot, rolling of the cockpit will always result in the intended "feel".

2. Suspension of Cockpit from a Point above the Pilot.

It was proposed to suspend the cockpit on a 12" diameter steel tube(See 1AHS15-17) mounted in gimbals some 3 feet above the cockpit and use the force loading mechanism as a counter balance(assuming them both to weigh 3000 lbs.). Loads from the force loading pistons would be transmitted by a mechanical linkage, through the center of the main

steel supporting tube, to the pilot's controls.

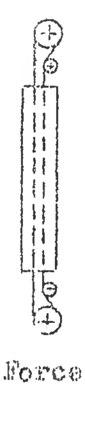


Elevator Control System - Figure 1

In order to do this, it was necessary to employ long, light-weight tubes through the steel tube. To avoid failure in compression and at the same time keep the weight of this portion of the linkage (thereby the inertia forces imparted to the pilot's controls) at a minimum, it was decided to use dural tubing of large diameter and small wall thickness (3.5" diameter, .093" wall thickness). In a layout of this cockpit mounting(Drawing L-37501) showing maximum pitch and roll angles of 30°, it was determined that the length of the control column tubes would be approximately 23 feet. Calculations(LJB510), showed that after keeping the weight and size of the tubes at a desired minimum, they became critical in compression at 16 feet.

3. Substituting a Chain Drive for Tubes in Control Mechanism.

A chain drive was investigated for control forces, but the diameter of the sheaves makes it necessary to raise the floor level of the force loading equipment(Drawing L-37502) to allow free rotation of the sheave. Assuming a 20" diameter sheave, it would be necessary to raise the force loading piston approximately 4". Considering the fact that such a system would require feeding the chain into the tube over a



Chain Drive from Force Loading Piston - Figure 2

small pulley supported on the upper and lower edges of the main supporting tube and that the angles that the chain makes with this pulley approach 90 degrees, it can be seen that this small pulley and its shaft must take objectionably high loads. These loads would probably be in the order of 7000 lbs. depending on the diameter of the sheaves.

Another objection to such a system is of course the lag or back lash which might be reasonably expected.

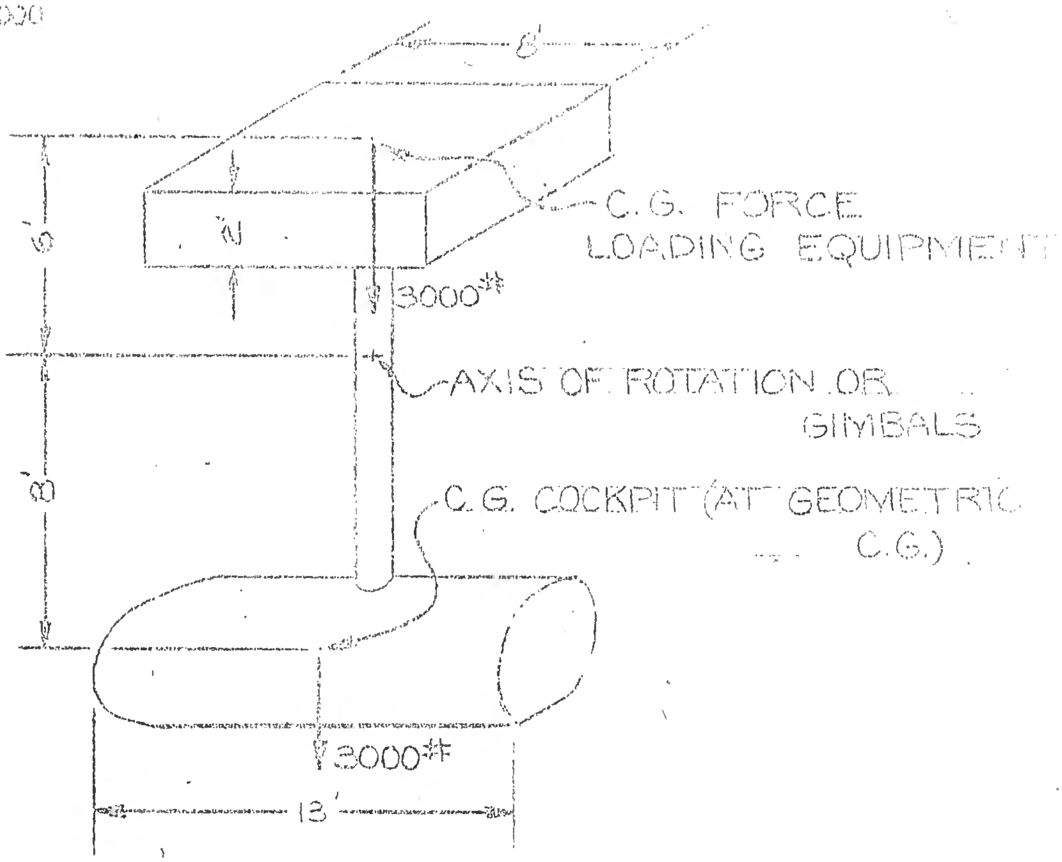
4. Suspension of the Cockpit from above. Force Loading Equipment Mounted inside Cockpit.

A system was investigated where the force loading equipment was to be mounted inside the rear portion of the cockpit and connected directly to the pilot's controls. However, under such conditions, it is reasonable to assume that the operating noise of the force loading equipment might be heard over the simulated engine noise and prove highly disconcerting to the pilot. It is also considered desirable to be able to interchange cockpits. If the force loading equipment were placed in the cockpit, it would be necessary to construct a separate set for each cockpit. These reasons seem to be sufficient to omit any further discussion of such a system.

5. Modification of Second Method.

The best method of mounting seems to be as shown in Drawing L-37501. It was decided to reduce the pitching angle to 20 degrees, move the supporting gimbals up to the level of the ceiling, shorten the original length of the cockpit, and change the shape of the rear of the cockpit to allow full $\pm$ 20° pitch. (Drawing D-37504). By so doing, it reduces the length of the main supporting column, the total moment of inertia of the system, and the dimensions of the hole in the ceiling where the gimbals are to be mounted. It was determined by measurement from the layout (Drawing D-37504), that the length of the vertical control tubes could now be reduced to 14 feet which puts them well within the critical length of such a system. At the present time this seems to be the most desirable method of mounting.

All calculations on this work were with estimated weights, center of gravity positions and angular accelerations.



Angular Accelerations in Pitch and Roll = One Radian Per Second.

B) - 1. Method of Actuating Cockpit in Pitch and Roll.

The most satisfactory means of pitching and rolling the cockpit seems to be through the use of hydraulic pistons as the hydraulic system is best suited to the type of servo control to be used in this case. Calculations show that only two pistons will be necessary for each plane of motion: one for pitch, and one for roll(1JBS27). The pistons may be mounted from the floor and attached to the main supporting tube by universal joints and a yoke as shown in Drawing D-37503.

2. Method of Vertical Motion.

Vertical motion of the cockpit has been investigated considering ± 6 inches as being sufficient motion to impart "feel" of small normal forces to the pilot. Such a motion may be represented through the use of 4 hydraulic pistons mounted as shown in Drawing D-37503. The main supporting tube now slides on roller bearings inside a short collar which is mounted on the gimbals. Calculations show that the only value of such a vertical motion might be in simulating extremely short period vibrations or normal accelerations(1JBS22-23). The practicality of vertical motion must be investigated further. It is considered impossible to duplicate conditions of even midly rough air or the effects of buffeting in a stall

without unreasonable amounts of vertical displacement. It is undetermined as to how small a normal acceleration may be felt by a pilot.

Engineer: James B. Smith

Approved by: Jay W. Forrester

JBS:has
March 18, 1946

L-37501	TOLERANCES NOT OTHERWISE SPECIFIED: DECIMAL ± .005 FRACTIONAL ± 1/64
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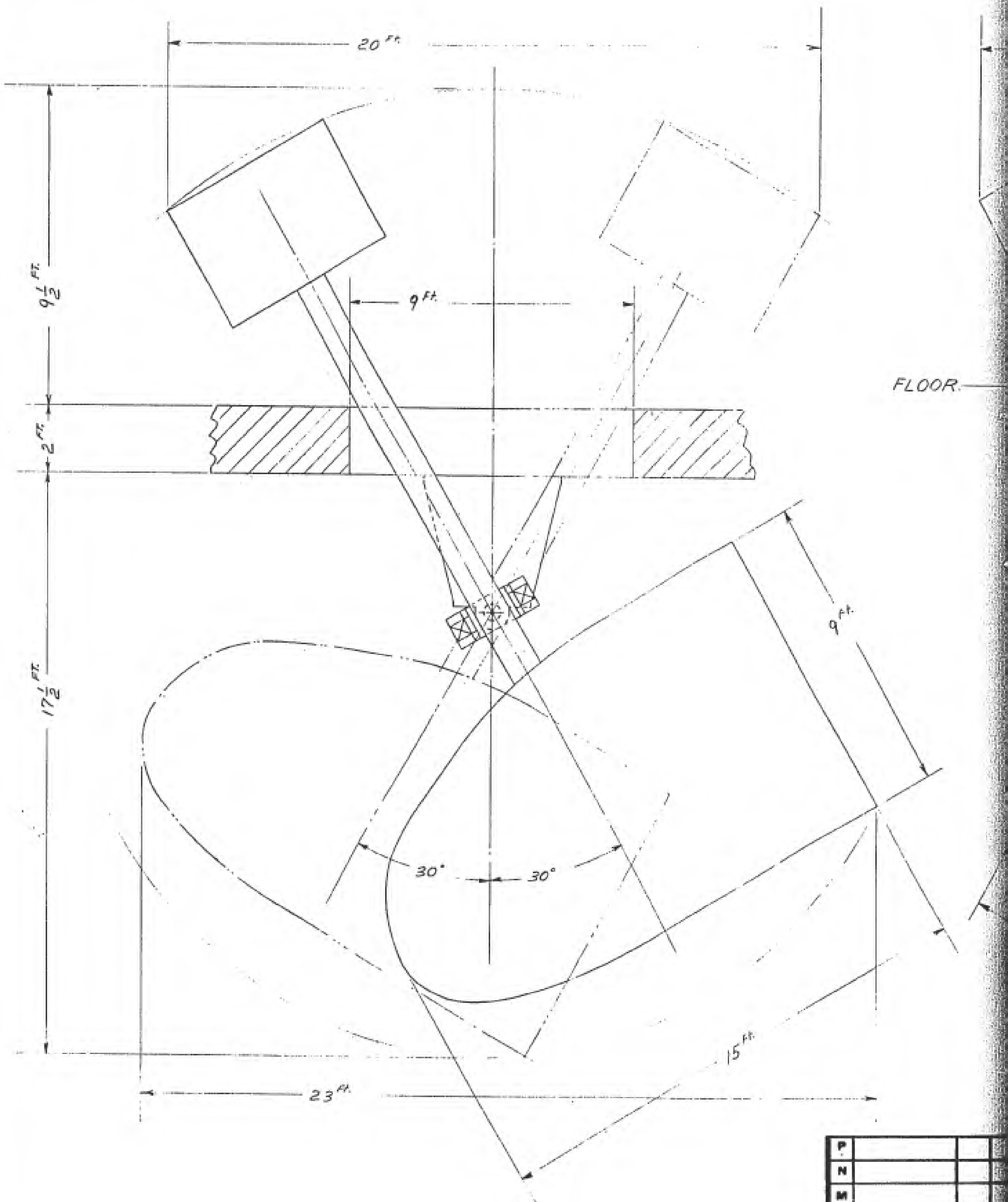

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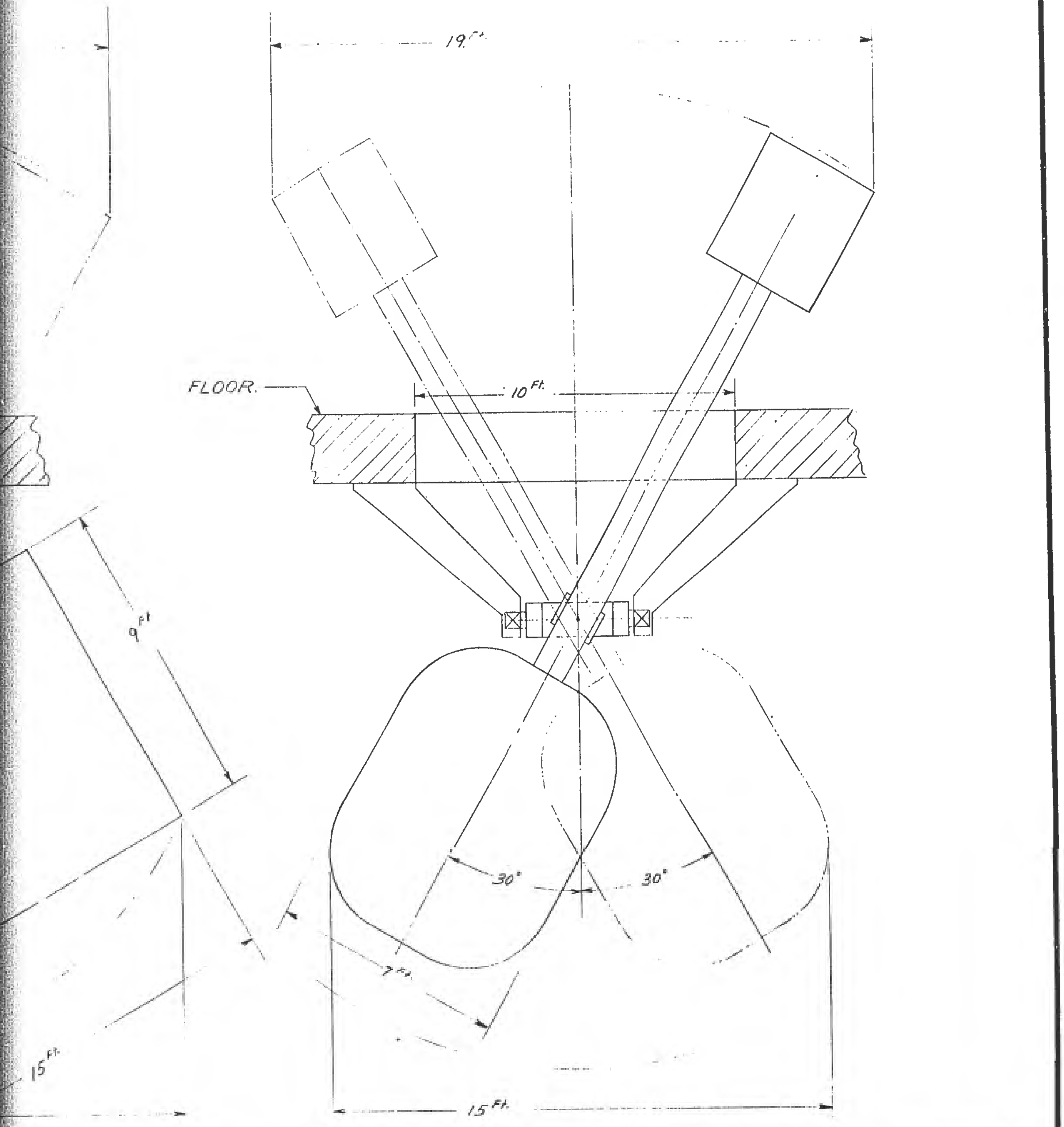

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ITEM	MATERIAL-DESCRIPTION	PART NO.	QUAN.

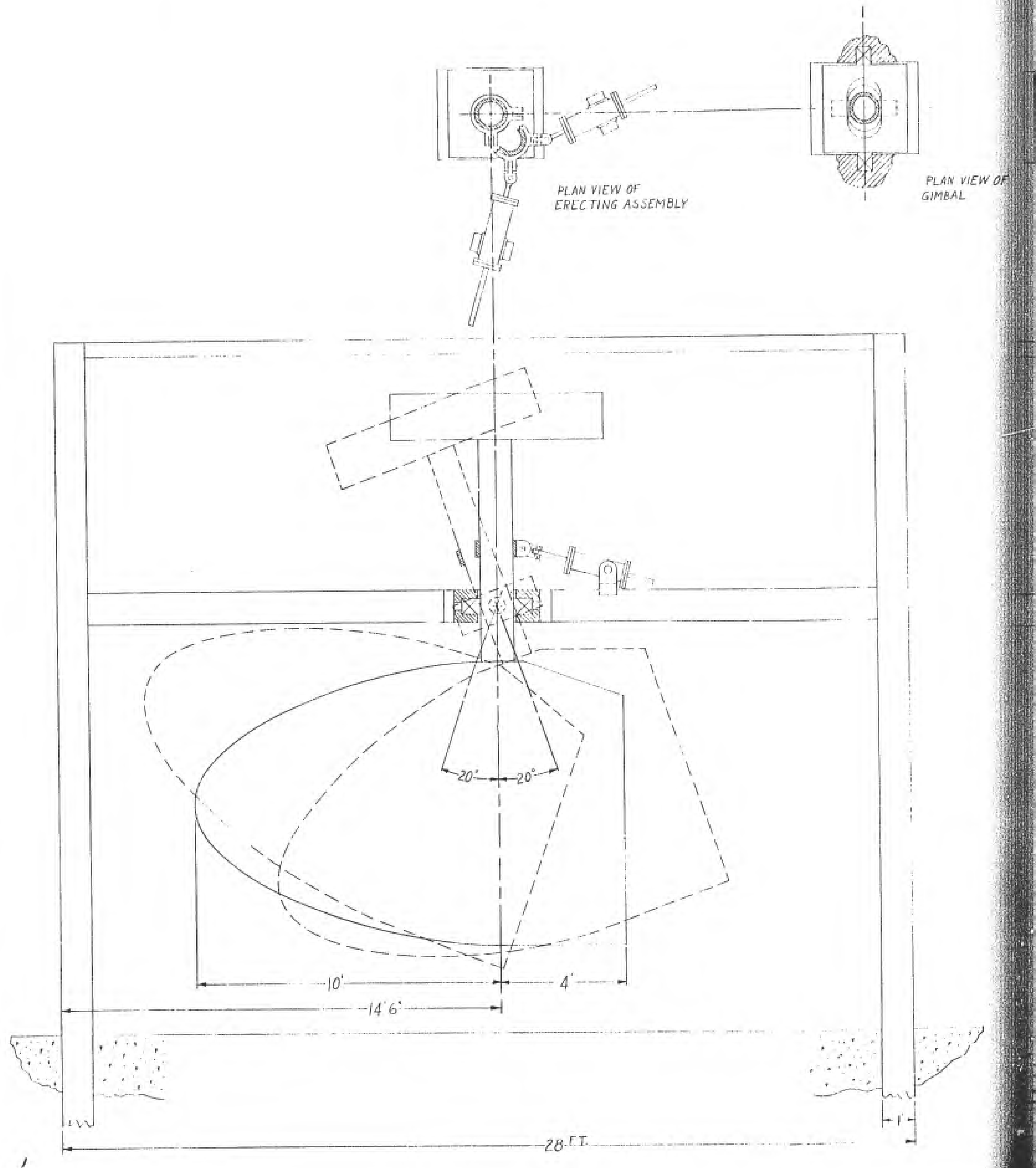
SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

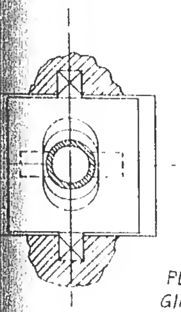
PROPOSED COCKPIT MOUNTING

SCALE: $\frac{3}{8}"$ = 1 Ft. DR. GRAFF 12-7-45
TR. CK. APP.

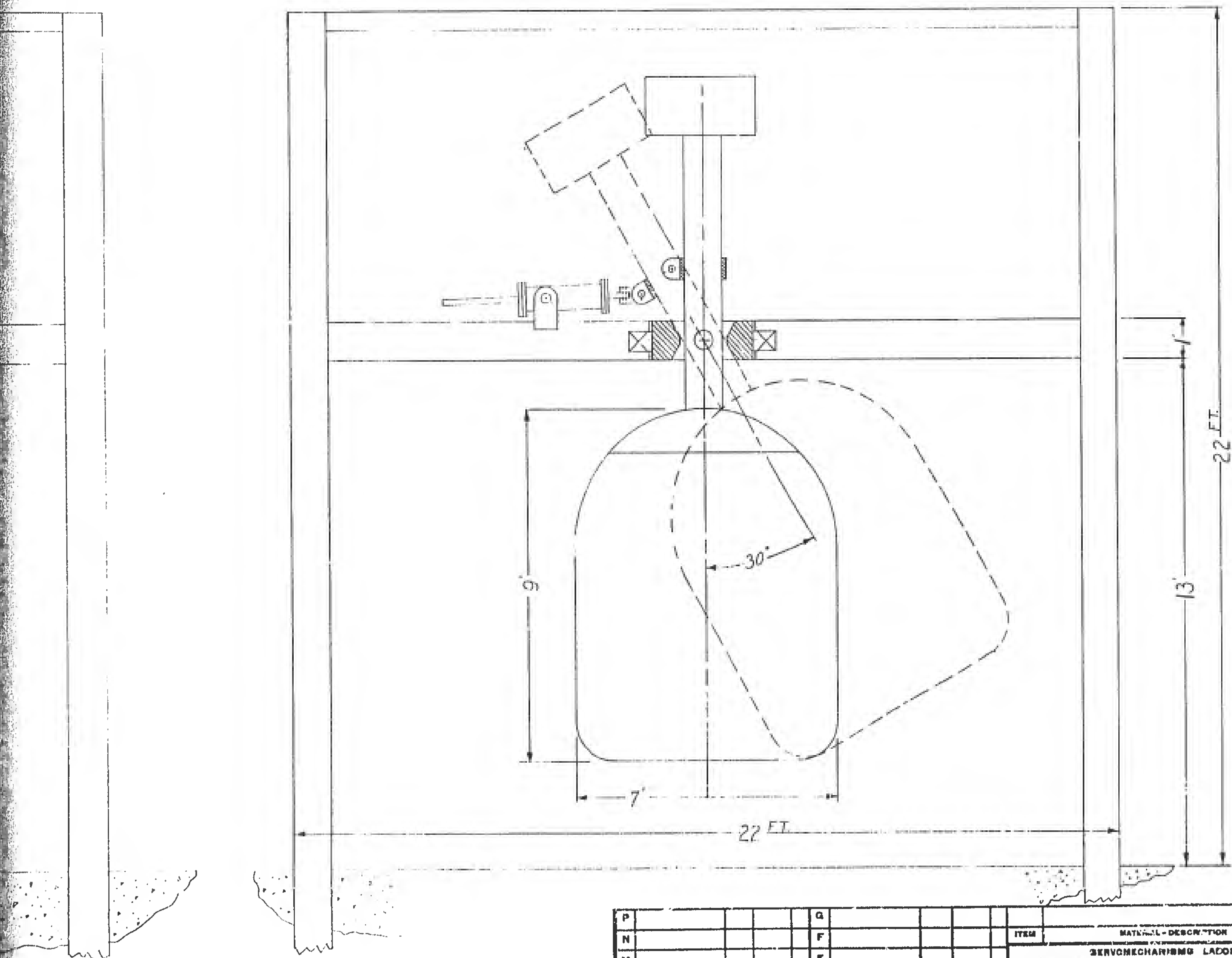
L-37501

D-37504	TOLERANCES NOT OTHERWISE SPECIFIED:
WO-	DECIMAL ± .005 FRACTIONAL ± 1/64





PLAN VIEW OF
GIMBAL



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ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

COCKPIT CONTROL ASSEMBLY

SCALE: $\frac{1}{2}$" = 1' DR. J. T. [illegible] Feb 13 '46
TR. CK. APP.

D-37504

MEMORANDUM M-74

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

To: 6345 Engineers

6345
Page 1 of 3 pages
Illustrations

From: Jay W. Forrester

Subject: Project Whirlwind Aircraft Cockpit Equipment

C-30557

Reference: R-99, Design of the Mechanical System for Transmitting Control Forces from Loading Equipment to Cockpit Controls by Alvin H. Shairman

R-100, Method of Cockpit Mounting and Actuating Mechanism by James B. Swett

Memo, from H. Fahnestock to Jay W. Forrester dated 12/19/45, "Proposed Simulation of Aircraft Accelerations in ASCA"

Date: May 9, 1947

One of the major objectives of the Project Whirlwind computer and associated equipment is the study of stability and control in large aircraft. The study of aircraft stability and control is essentially one of simulation since the objective is to permit a test pilot to evaluate the performance of an airplane which has not yet been constructed. This simulation will be accomplished by using the electronic computer for calculating the response of an airplane based on inputs received from the controls in a simulated airplane cockpit. This cockpit is shown in relation to the other equipment of Project Whirlwind in drawing No. C-30557.

In operation the pilot flies the airplane using equipment in the cockpit just as he would fly a real aircraft. He moves the various controls available in the aircraft cockpit and in response to the motion of these controls, the electronic computer calculates what the aircraft under study should do. This information from the computer is converted into instrument readings which the pilot can observe and into signals to the control force loading equipment which will provide to the pilot proper feel on the aircraft elevator, aileron and rudder controls. At the same time, signals will be sent from the electronic computer to tilting mechanisms for providing motion to the aircraft cockpit. This motion will not be that of the real airplane in space but instead will be the motion necessary to provide in the cockpit a feel of the proper direction of acceleration. For example, a properly banked turn will result in no motion of the cockpit while on the

other hand, yaw, side-slip and other accelerations will result in tilting of the cockpit to provide the proper direction of total acceleration. It will, of course, be impossible to alter, except for transient changes, the magnitude of acceleration force on the pilot since this force will be limited to the pull of gravity.

Equipment unique to the aircraft analyzer cockpit phases of Project Whirlwind can be considered in five divisions.

1. Structure
2. Instruments
3. Control Force Loading Equipment
4. Cockpit Tilting Equipment
5. Digital Conversion Equipment

The above phases of the program will be considered individually.

1. Structure

Under Structure we will include not only the cockpit frame and body itself but also the supporting mechanism within which the cockpit is to be tilted. The cockpit shall have a normal interior and arrangement for a large aircraft. It shall be usable as either a two or four-engine design. In size and arrangement it shall be suitable for a pilot and a co-pilot in the operating positions and for three observers where they may see the flight instruments. Considerable attention must be given to producing realism and the cockpit shall be complete with noise and vibration generators responsive to the engine controls. Radio headphones will connect to an intercommunication system available at other parts of the Whirlwind computer.

Pickoff devices must be installed on all mechanical controls for conversion of mechanical positions into signals for the electronic computer. The cockpit should not be arranged as any existing airplane, yet should follow the Army-Navy standardization plans for aircraft cockpit interiors. Included in cockpit phases of the program will be decisions on instrument arrangement, proper mounting of the cockpit including a study of the proper center of rotation about which the cockpit should be tilted to give best simulation of accelerations. Means must be provided for changing the cockpit to one of different interior design and arrangement

In the design of the cockpit, particular attention must be given to reduction of elasticity in the structure and the reduction of inertia and friction where these factors can affect the Control Force Loading Equipment and the transmission of these forces to the pilot's controls. Design of

the cockpit structure depends on associated equipment in the following ways

1. Instruments - instruments must be coordinated with the structure only in matters of arrangement and physical space for mounting.

2. Control Force Loading - the cockpit must provide suitable mounting methods for the CFL equipment. Transmission between the CFL equipment and the pilot's controls must be done without appreciable elasticity, backlash, or friction. CFL equipment should be demountable, should be easily accessible for servicing, and oil leakage from this equipment must not enter other parts of the cockpit.

3. Tilting Equipment - the cockpit structure depends on the tilting equipment only as related to the coupling of the two units for drive purposes and in so far as the structure must be designed to withstand the forces imposed upon it by the tilting equipment.

4. Digital Conversion Circuits - all mechanical controls in the cockpit, as for example, engine controls, must transmit their motion to conversion equipment suitable for delivery of digital numbers into the computer.

2. Instruments

Both mechanical design and instrument servo design are included. The number and kind of instruments in the cockpit must be established. Instruments associated with the engines will, if possible, be considered to belong to the engineer's station. This station may or may not exist in reality. A few basic types of instrument motions and corresponding servo drives should suffice for all instruments on the pilot's panel.

Most flight instruments can be simulated by a servomechanism driving an indicator through less than 180° of arc. An exception is found in the altimeter, compass, directional gyro, and some air speed indicators which makes several revolutions and where extreme sensitivity is required. Some

instruments can probably be satisfactorily simulated with electrical voltmeters.

Instrument design will depend in the following ways on other phases of the cockpit program:

1. Structure – instruments will depend on structure only in questions of space and mechanical arrangement

2. Control Force Loading – none

3. Tilting – none

4. Digital Conversion – the digital conversion equipment will provide input signals to the instrument servos. The data systems must be coordinated.

3. <u>Control Force Loading System</u>

The Control Force Loading System is a hydraulic mechanism providing the proper forces on the cockpit rudder, aileron, and elevator controls. In providing realism and in evaluating the behaviour of aircraft, the Control Force Loading Equipment is considerably more important and critical than the cockpit tilting equipment.

An operating mechanical breadboard of the Control Force Loading Equipment exists at the present time. Operation of this equipment is nearly satisfactory Tentative layouts for a new packaged system prepared by Rider and Graff are in the drafting room.

Additional work on the present system is necessary to improve the pressure regulating valves for reduction of vibration and to reduce their operating force dependence on oil flow. Some tentative value designs have been prepared but not tested. An improved hydraulic amplifier may be desirable and measurements of servo loop gain and response should be made on this system. The electronic amplifiers and perhaps the data system should be revised and a suitable size of main drive motor selected.

To the equipment now existing must be added remotely controlled elasticity and Coulomb friction between the pilot and the control surface. A converter for giving control position in binary numbers must be provided and a strain gage signal made available to the digital converter for transmission of the control column forces to the output recorder of the computer. Design of the Control Force Loading Equipment will depend on the following phases of the program.

1. Structure - space must be provided in the cockpit for the Control Force Loading Equipment. Control Force Loaders should be packaged units readily accessible for servicing and exchange to other cockpits. They should be so arranged that oil leakage cannot reach other parts of the cockpit. Connection between Control Force Loading Equipment and the control columns in the cockpit should be through push rods with careful attention given to reduction of elasticity and friction. For proper operation of the CFL equipment, inertia in the control columns must be held to a minimum.

2. Instruments - none

3. Tilting - none, except for the effect that weight, shape and location of the CFL equipment will have on the dynamics of the cockpit tilting system.

4. Digit Converters - the CFL equipment receives data on required force and transmits column position. The CFL mechanism must drive a suitable high sensitivity digit converter.

4. Tilting Mechanism

Design of the cockpit mounting and design of the cockpit tilting equipment must be preceded by a study of the magnitudes and directions of accelerations to be expected in large aircraft. Results of this study will set specifications for the tilting equipment. It will be necessary to know the transient characteristics of accelerations to be expected as well as their maximum values.

Design of the cockpit support and mounting will depend upon how high the cockpit pivot point should be above the location of pilot and co-pilot.

Servo design must be such as to provide sufficient power and approximately the accelerations indicated by the above study. Operation of the servo system must be smooth but accuracy can be low since tilting of the cockpit is provided only to increase the sensation of actual flight. Tilting will provide the proper direction but of course not the proper magnitude of apparent gravity.

In designing the cockpit it is desirable to keep the required building ceiling height low. From consideration of the tilting servos, the pivot should be near the center of gravity of the cockpit; but probably from consideration of the feeling produced, the pivot should be above the cockpit compartment. Questions of statically balancing the cockpit as against forcing the tilting servo to work against cockpit unbalance must be considered.

Mounting of the cockpit might be by cable suspension from an overhead X-frame; by support on hydraulic cylinders; or by attachment to a pivoted column. The tilting equipment will depend on.

1. Structure – for inertia, unbalanced forces, and rigidity as well as the mechanical coupling design.
2. Instruments – none
3. Control Force Loading – the loading equipment will affect tilting only as it may be used for counter balancing the cockpit and insofar as inertia of the CFL equipment will affect the tilting servos.
4. Digit Converters – the tilting equipment receives its control data from the computer.

5. Digit Conversion

Digit conversion may be considered in two sections:

A. Conversion of digits to electrical signals

B. Conversion of mechanical motions to digits

Considering first the Conversion of Digits to Electrical Signals, the following table shows the relative sensitivity and accuracy required in different applications.

	High	Good	Fair
Sensitivity	Altimeter	Other instruments	Tilting and Control Force Loading
Accuracy		All instruments	Tilting and Control Force Loading Equipment

The kind of output voltage to be delivered by the converter must be correlated with the various servo requirements. All incoming data will be over a single set of digit buses from the computer and proper switching must be provided in the digit conversion to make the output signal voltages available at the proper servo systems. To reduce equipment it will be highly desirable that a single digit to voltage converter be used with a simple switching system for distributing the resulting voltages into the proper channels. Switching will be operated under control of the computer. Data will be delivered at intervals ranging from 1/2 second to 1/100 second, and the signals delivered to the servo mechanisms must be satisfactorily smoothed.

B. <u>Mechanical</u> <u>to</u> <u>Binary</u> <u>Order</u>

A system of this type might for example consist of D.C. potentiometers attached to all mechanical shafts in the cockpit. Voltages from these lines might then be switched into a single converter which will provide the necessary binary digits for use by the computer. It will be desirable for the switching and conversion to operate in the same manner as the electronic computer storage which means that an interval of approximately 6 microseconds will be available for the selection and conversion of information ready for use by the computer. The following tabulation shows sensitivity and accuracy required by various cockpit equipment in the conversion of mechanical motions to digits. Indications are relative and actual figures must result from further study.

	High	Good	Fair
Sensitivity	Elevator, Aileron, Rudder	Controls for Engines, Tabs, and Flaps	
Accuracy		Control Force Loading	Flaps, Tabs, and Engine

Design of the digit converting equipment may be done as part of the computer rather than as part of the cockpit system. However, the digit converting equipment will depend on other phases of the cockpit program in the following ways:

1. Structure - space in the cockpit structure must be provided for the mechanical to binary conversion transmitters.

2. Instruments - design of the digit conversion equipment must be coordinated with the data transmission system of the various instruments and servo mechanisms.

3. Control Force Loading - the digit converting equipment will supply forced data to the CFL equipment and will receive shaft positions and control forces for transmission to the computer.

4. Tilting Equipment - the digit conversion must supply signals to the tilting mechanism.

Cockpit Design and Construction Program

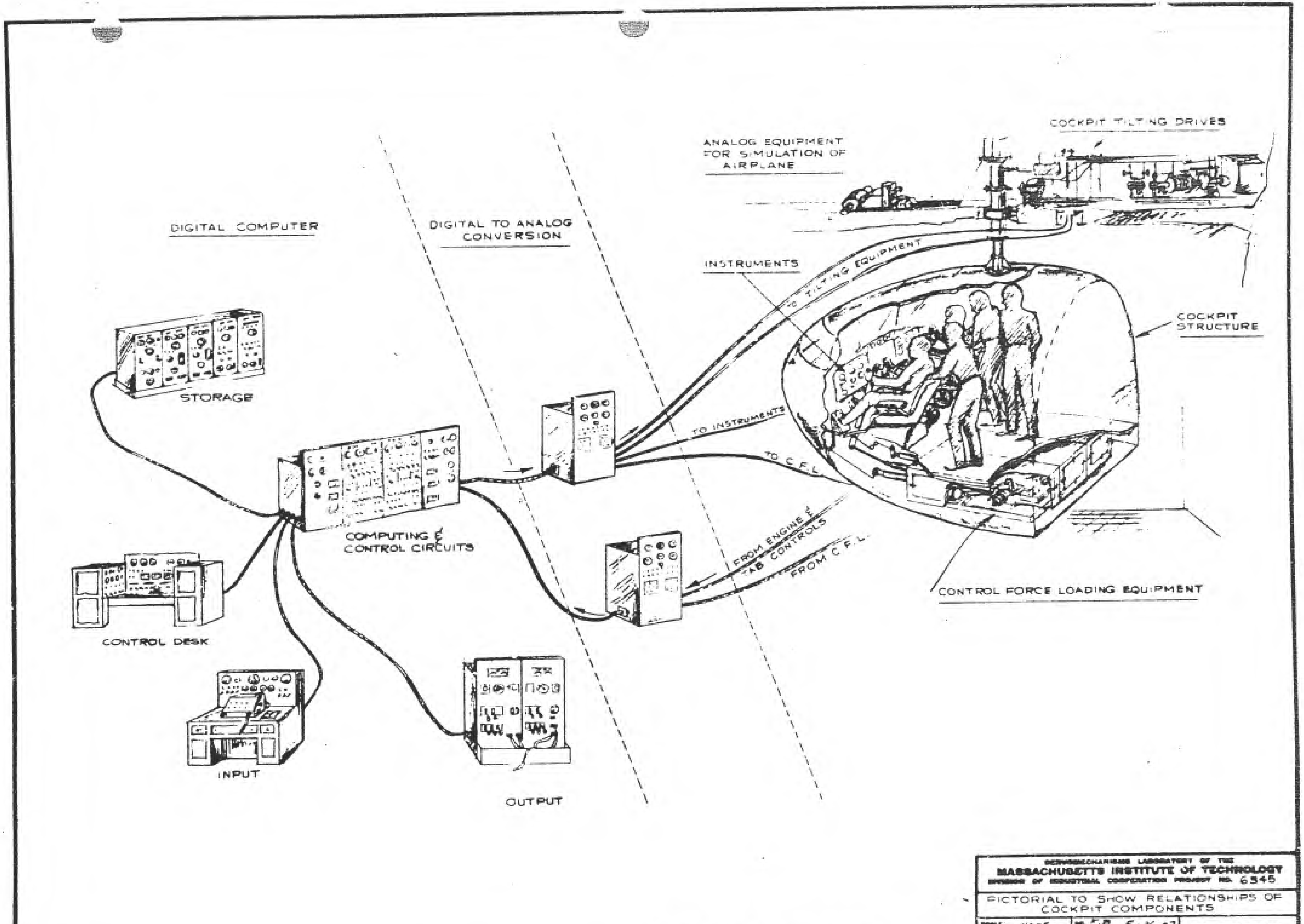
It is highly desirable in the Project Whirlwind Program that the cockpit and associated equipment be designed and constructed by June 1948. To make this possible, immediate steps must be taken in the selection of the required sub-contractors, in the specification of details which can now be established and in such research and development work as remains to be done.

The cockpit and its associated equipment will be extremely valuable when used with the Whirlwind I computer for evaluation of many questions relating to the large scale Whirlwind II and its use for the solution of aircraft stability and control. The techniques required for the cockpit simulation will be required in other training and control devices.

Jay W. Forrester

JWF:vh

cc: G. Malhmann
P. Tilton
C. R. Wieser



USED IN 6345 REPORT R-125

SERVOMECANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts
Memorandum M-85

To:	R. R. Everett, C. R. Wieser, H. Fahnestock, P. D. Tilton, E. S. Prohaska		
From:	George H. Graff		
Subject:	Recapitulation of Work Done on Design of Cockpit Assembly		
Date:	June 30, 1947		
References:	6295 Report	6	Throttle Valve
	" "	22	Preliminary Investigation of Summing Circuits.
	" "	29	Summing Amplifier, Electronic
	" "	36	Description of Proposed Control Force Demonstrator
	" "	37	Control Column Loading Equipment--Analysis of Component Parts.
	" "	38	Control Column Loading Equipment-Stability and Gain of Proposed Closed Cycle Schematic
	" "	49	Numerical Ranges of Aircraft Stabilizer Computer Analyzer.
	" "	58	Control System Information
	6345 Report	R-99	Design of Mechanical System for Transmitting Control Forces from Loading Equipment to Cockpit Controls.
	" "	R-100	Method of Cockpit Mounting and Actuating Mechanism.
	Summary Report #1		
Drawings:	~~R-20342~~		Force Analyzer Assembly
	~~L-37500~~		Proposed Cockpit Mounting (obsolete)
	L-37501		Proposed Cockpit Mounting (obsolete)
	~~L-37502~~		Cover Plate Assembly
	L-37503		Cockpit Column Control
	L-37504		Cockpit Control Assembly
	~~L-37505~~		Proposed Sump Assembly
	C-30047		Elevator Control System
	C-30048		Rudder Control System
	C-30049		Aileron Control System
	C-30053		A.S.C.A. Cockpit Mounting (Perspective)
Notebooks:	Harris Fahnstock		Notebook #1
	George H. Graff		Notebook #1
	C. H. Rider		Note ook #1
	Alvin E. Shairman		Notebook #1

General Description of Cockpit Assembly

The cockpit is to be a replica of one in a real aeroplane, able to simulate the movements of flight and with controls that are loaded and have the feel as in flying. The aim is to give the pilot the illusion of flying while he operates the controls in order to get his reactions and test his ability to keep the plane under control.

Data relative to actual cockpit performance and description of actual control systems with forces involved in flight was furnished by the Wright Brother's Wind Tunnel and is contained in Reports 449 and 58.

A perspective drawing of the equipment as finally decided upon to accomplish this aim is shown on drawing C-30053. It consists of a hollow vertical column mounted on gimbals in its middle portion, on the lower end is hung the cockpit, on the upper end is placed the platform containing the three force loading units for loading the rudder, elevator, aileron controls respectively. Linkage running thru hollow column connects force loading equipment with controls. Four hydraulic cylinders located on middle floor of building impart motion to cockpit; one for roll, one for pitch, and two for vertical motions.

The cockpit project may be divided into 5 parts for convenience of discussion. They are as follows.

1. Cockpit
2. Force Loading Equipment
3. Linkage between Loading Equipment and Controls in Cockpit
4. Cockpit Activating Equipment
5. Assembly of above Parts with Column and Mounting on Gimbals

I shall take up each part separately giving the state of development up to the present time.

1. Cockpit

No design work has been done on the cockpit. However some information and specifications relative to its design have been accumulated in Mr. Fahnestock's and Mr. Rider's notebooks.

Mr. Fahnestock's Notebook #1 contains information under the following headings.

Cockpit Equipment

Responsibility for Installation of Cockpit Equipment

Arrangement of Controls and Indicators

Instruments - Data Source and Type

and from Mr. Rider's Notebook #1

Listing of Cockpit Instruments, Number Required with Operating specifications and Apparatus.

Listing of Cockpit Controls, Number Required, Comments on use of Standard Parts

Listing of Inoperative Equipment, Number Required

Listing of Outputs from Cockpit

2. Force Loading Equipment

An hydraulic system for generating the control forces was devised and a demonstrator model to check the worth of the system was built. The demonstrator is shown on drawing R-20341 and described in report 36. Analysis of component parts and stability and gain of system are given in reports 37 and 38. Tests having proved the worth of the system, that portion of it to be mounted with the cockpit was redesigned with the aim of making a compact, packaged unit.

This design differs from the demonstrator by the use of

two adjustable dampers to simulate friction torque instead of tachometer, by the addition of two compression springs in linkage to simulate cable stretch, and by new design of regulating valves.

The unit consists of a rectangular tank with cover plate. Layout drawing of tank and equipment mounted in it is L-37505. Figure 1 shows this equipment schematically. Tank is 3/4 filled with oil.

On the underside of the cover (layout L-37502) is mounted the equipment for governing the oil supply to the power piston. This is shown schematically in figure 2. Not shown on schematic is coil of copper tubing thru which water circulates to cool the oil.

The main oil supply for the power piston is furnished by two Vicker's 2 - stage vane pumps mounted on opposite ends of a common drive motor. Pumps and motor are mounted independently of the tank.

The force loading equipment consists of 3 tanks with cover plates and 3 motors each mounted with twin pumps all mounted on a platform which is set on top of hollow vertical column. This equipment serves as a counterbalance to mass of cockpit swinging on lower end of column. It is estimated that the 3 units (3 tanks, 3 motors with pumps, and oil) will weigh approximately 4600 pounds. The platform will be approximately 10 ft. square.

Twin compression springs to simulate cable stretch are designed for a maximum torque of 400 ft. lbs. with spring gradients ranging from 25 ft. lbs. per degree to 500 ft. lbs. per degree. Design calculations in Graff's Notebook.

Each friction torque damper is designed for 0 to 60 lbs. of torque, Design calculations in Graff's Notebook. An undesirable characteristic of this design is that below certain velocities the friction torque will fall short of that desired because of unavoidable leakage around piston and valve.

Tests were run with a control valve with 90° included angle of valve face (A-20372-3) with varying values of valve spring force. Results have been tabulated - oil pressure versus flow - in A. H. Shaizman's Notebook on page 11. After these tests a new design of valve and valve body was developed using a piston type valve. This is shown on drawings B-30043 and B-30044. Experimental model has been built but as yet no tests have been run.

Data Used in Design of Force Loading Equipment

Max. oil pressure 2000 lbs. per in^2 (Main oil supply)

Min. oil pressure 300 lbs. per in^2 (Main oil supply)

Max. diff. pressure 1700 lbs. per in^2

Area under pressure 2.77 in^2

Angle of travel of output shaft $\mp$ 22 1/2°

Max. force exerted by piston 4720#

Max. torque 2560 ft. lbs.

Normal operating acceleration of controls about 100 radians per sec^2

Max. operating acceleration of controls about 800 radians per sec^2

Ratio Gear Train for Glass Disc - 25

Ratio Gear Train for Tachometer - 10

Oil pressure to hydraulic amplifier 300 lbs. per in.^{2}

The force loading equipment as designed is heavy and bulky in spite of efforts to make each unit compact. Possibly by using one sump and one oil system common to all three units the volume and weight can be reduced. The Vicker's twin pump and motor assembly account for 1/3 of the total weight.

3. Linkage Between Loading Equipment and Controls in Cockpit

This linkage is designed schematically. Overall dimensions of main connecting rods are determined. Much design work still remains to be done. Report R-99 with drawings C-30047, C-30048 and C-30049 describe the work done up to this time.

4. Cockpit Activating Equipment

This equipment is shown schematically on drawings L-37503 and L-37504 and is discussed in report R-100 section B. Only the surface has been scratched on this phase of the project. Movement of cockpit in pitch of $\pm$ 20°, and in roll of $\pm$ 30° with accelerations in both cases of one radian per second per second have been fixed upon. However the vertical movement of cockpit has not been decided upon either in amplitude or acceleration. That the motion will be produced by hydraulic cylinders is fairly certain, but the design of the hydraulic system and linkage connecting it to column is in an embryonic condition.

H. Fahnestock's Notebook gives information relative to motion of cockpit under the following headings.

Flight Demonstrations

Proposed Simulation of Aircraft Accelerations

C. H. Rider's Notebook gives the following:

Angular motion, rate and acceleration of cockpit.

5. Assembly of Parts 1, 2, 3, and 4 with Column and Mounting on Gimbals.

This phase of project is concerned with arrangement of component parts and manner of suspension. The design fixed upon is shown on drawing D-37504 and is discussed in report R-100 section A. Gimbals, manner of fastening cockpit to column, and a platform for force loading equipment have yet to be designed. The size of hollow column was arrived at using 3000 lbs. each for weight of cockpit and force loading equipment. As a later estimate places weight of force loading equipment around 5000 lbs., column size should be redesigned.

GHG:ES
(Drafting Room)

Fig. 1 - Dwg. A-31155
Fig. 2 - A-31156

A-31155

USED IN 6345 MEMO M-85

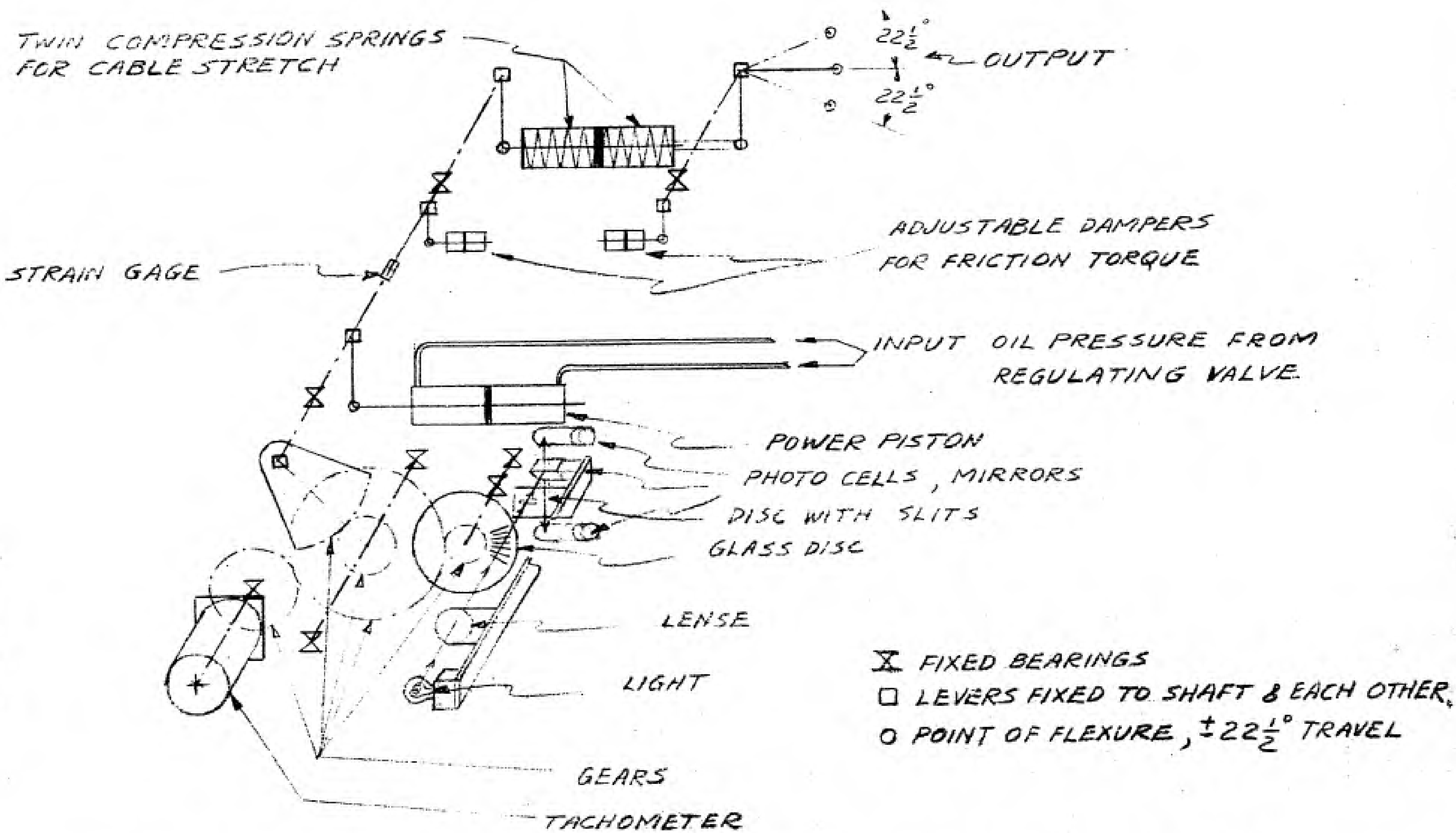
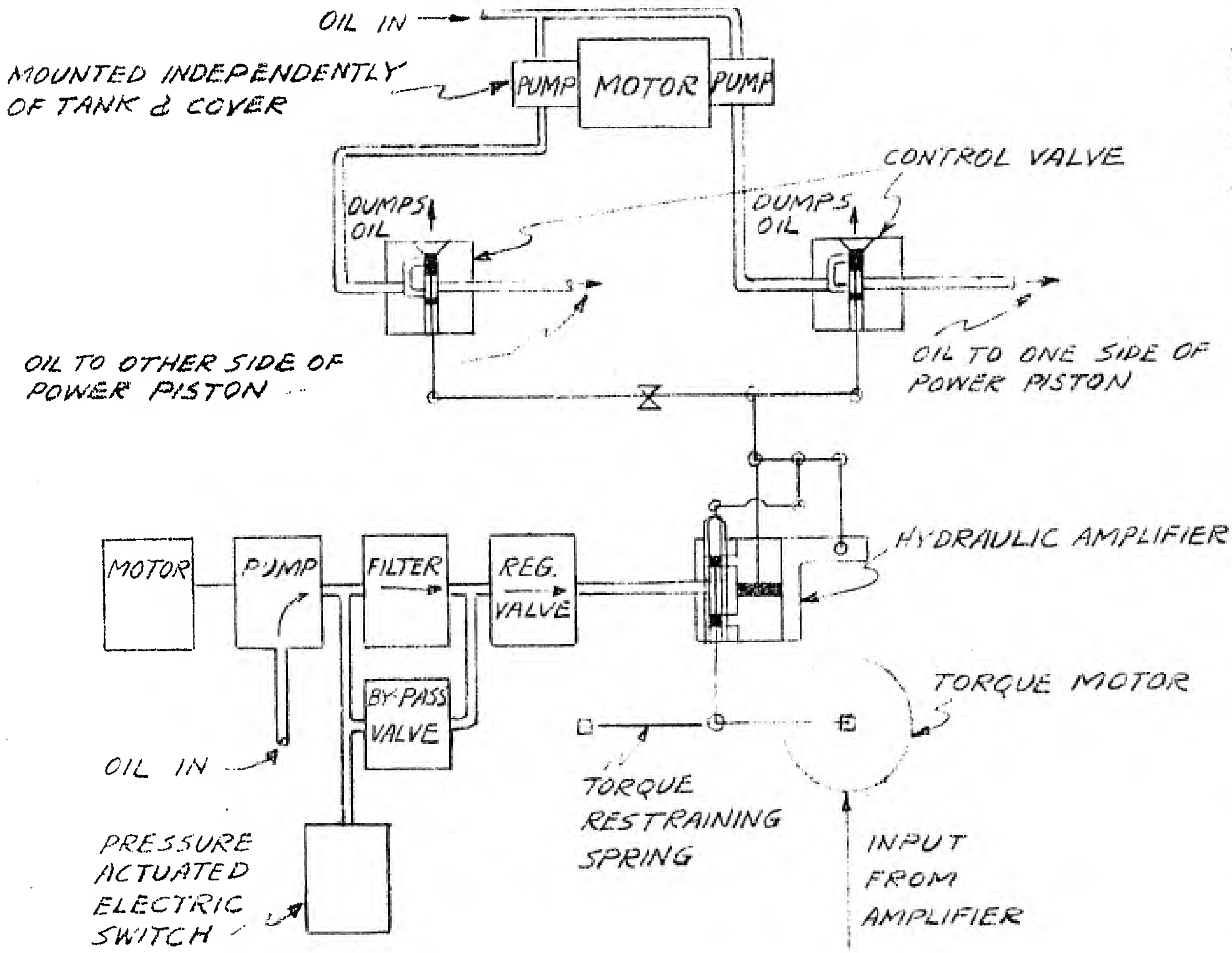


FIG. 1

SCHEMATIC OF EQUIPMENT MOUNTED ON TANK & SHOWN ON LAYOUT L-37505

GHG
6/24/47

A-31155



SCHEMATIC OF EQUIPMENT MOUNTED ON BOTTOM SIDE OF TANK COVER PLATE

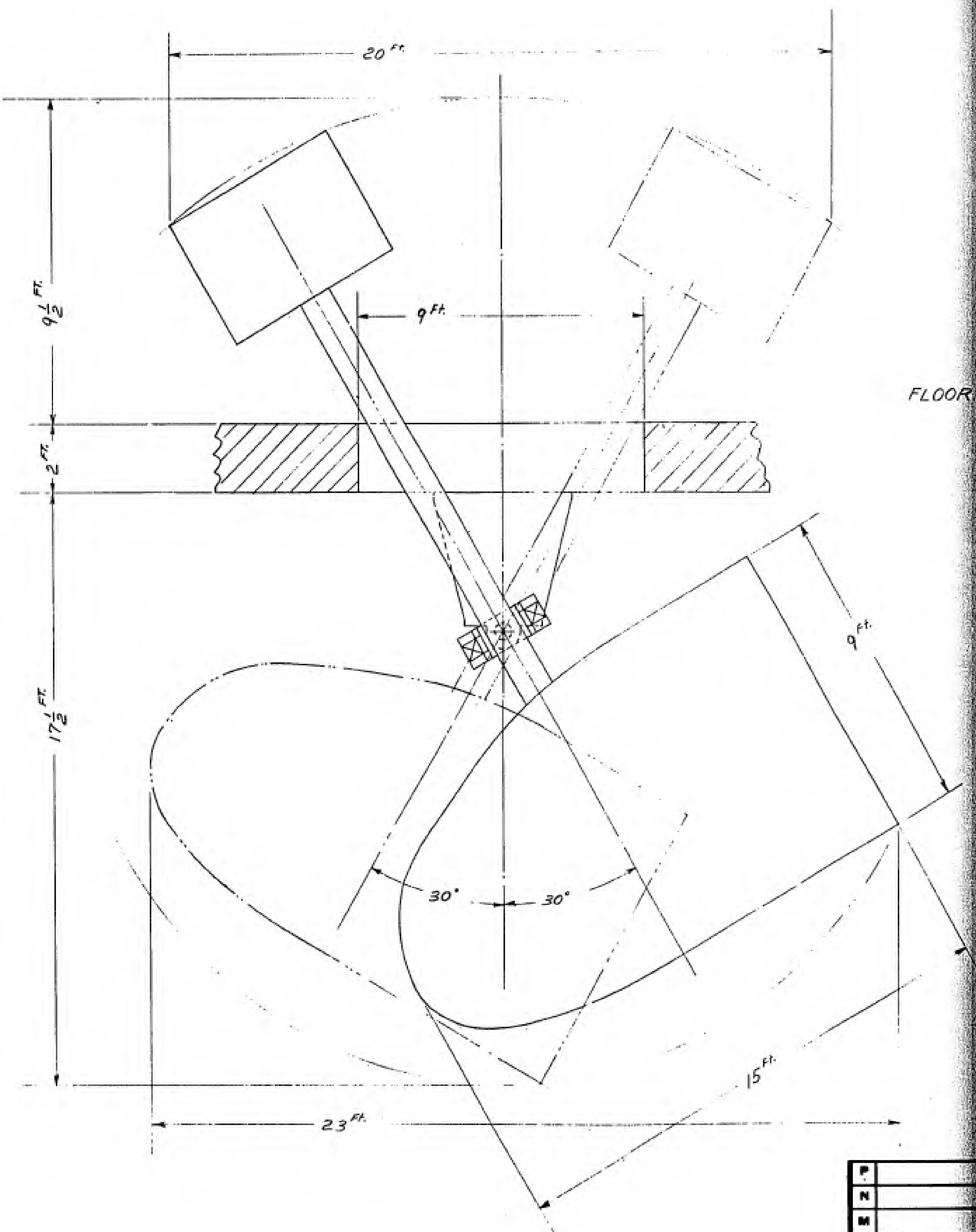
GHG
6/-9/47

FIG. 2

A-31156 USED IN 6345 MEMO M-85

A-31156

L-37501	TOLERANCES NOT OTHERWISE SPECIFIED: DECIMAL ± .005 FRACTIONAL ± 1/64
WO-	



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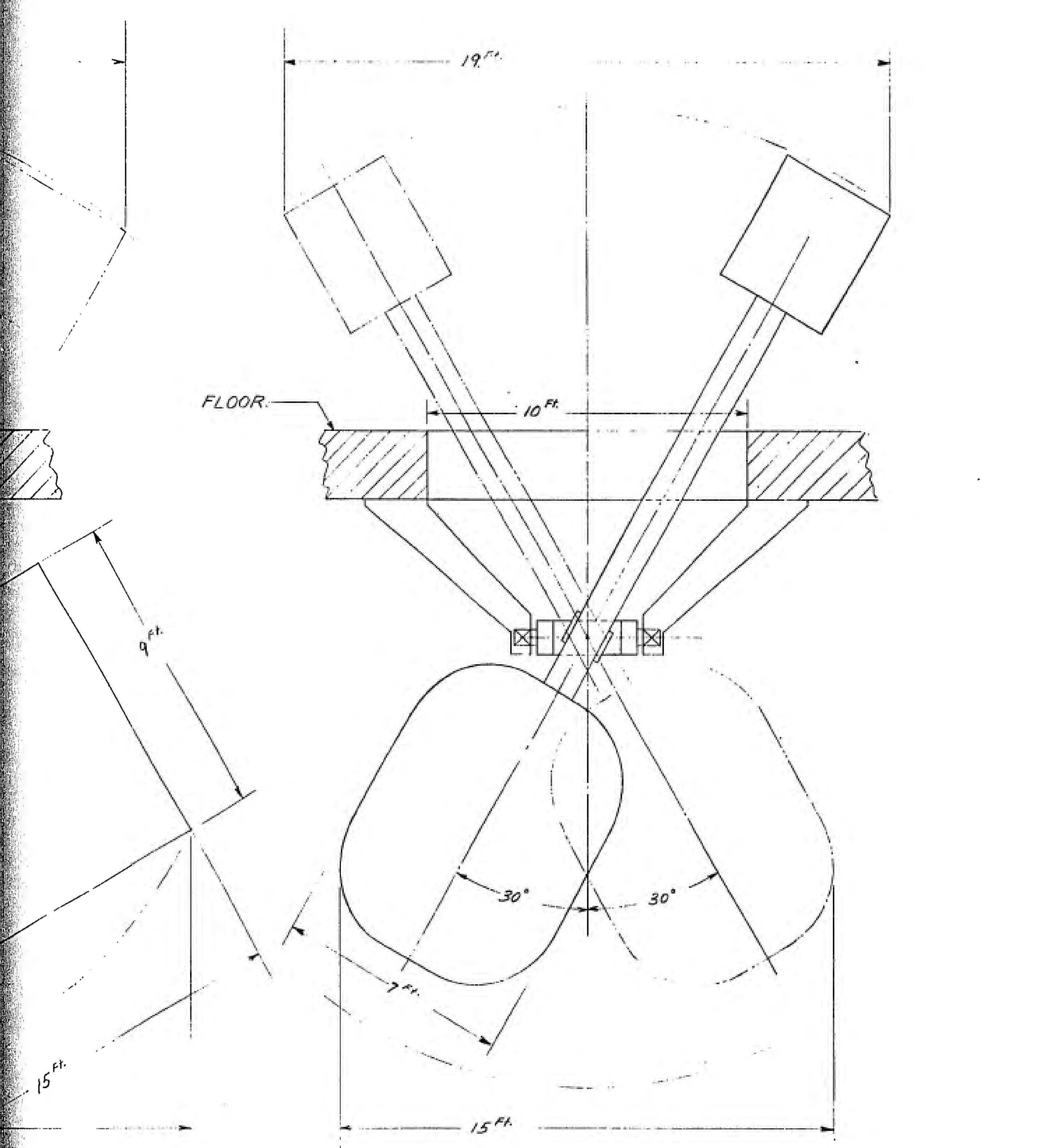

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K				C			
J				B			
H				A			
	WAS	APP.	DATE		WAS	APP.	DATE

ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

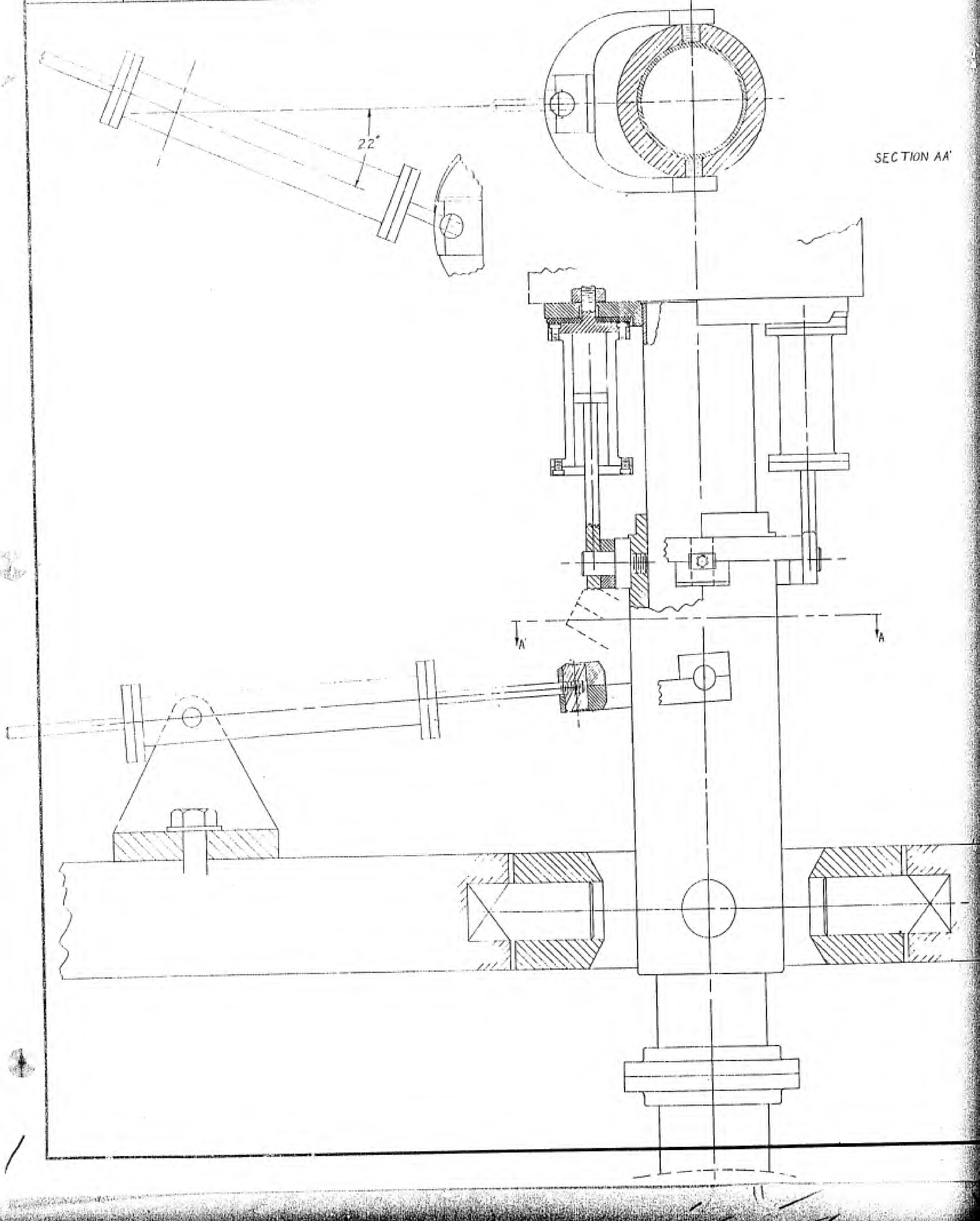
PROPOSED COCKPIT MOUNTING

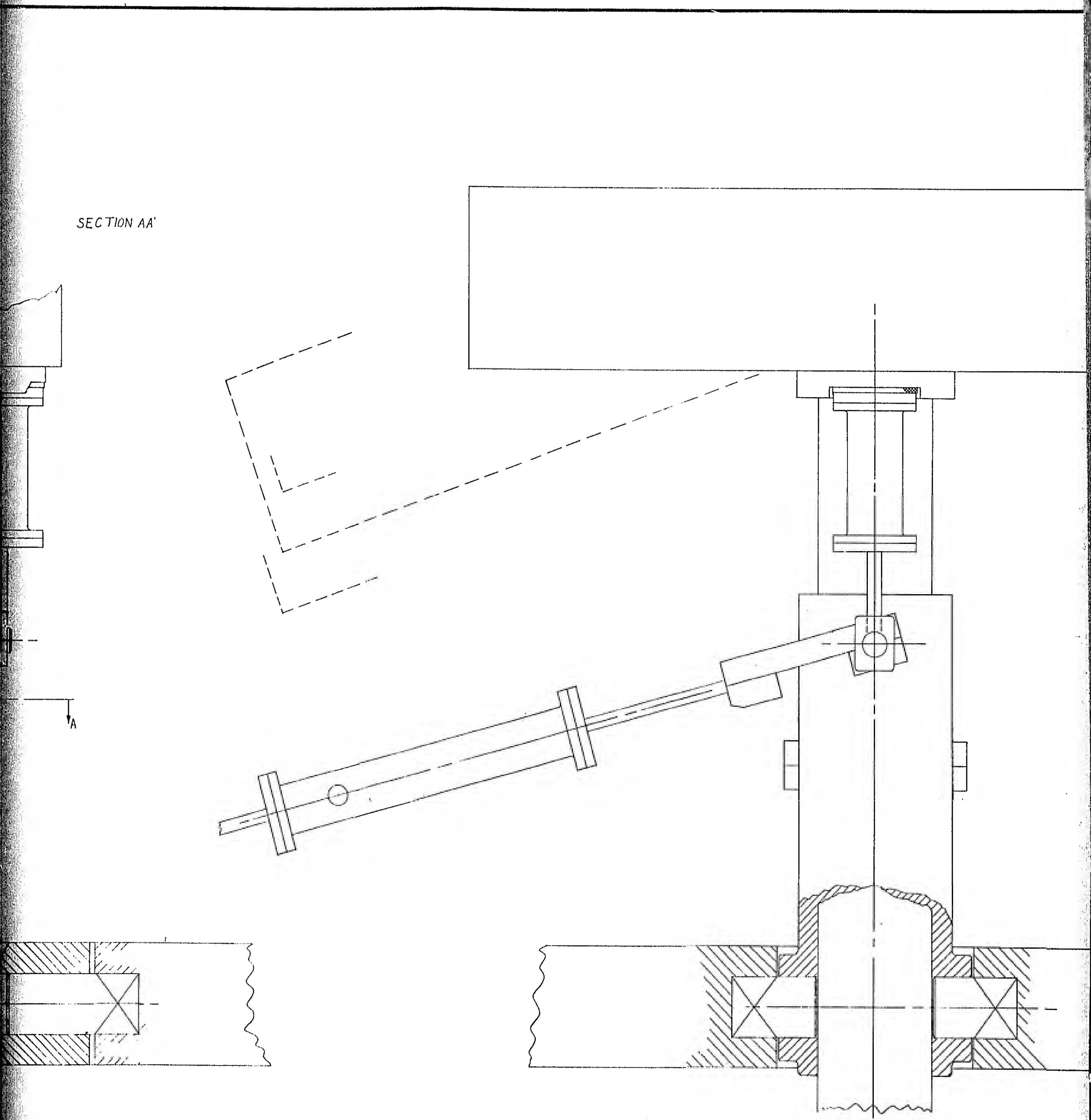
SCALE: $\frac{3}{8}$" = 1 Ft. DR. GRAFF 12-7-45

TR. CK. APP.

L-37501

E-37593 WO-	TOLERANCES NOT OTHERWISE SPECIFIED: DECIMAL ± .005 FRACTIONAL ± 1/64





P N M L K J H — WAS APP. DATE

G F E D C B A

A 6 PISTONS MAR21'46

WAS APP. DATE

ITEM MATERIAL-DESCRIPTION PART NO. QUAN.

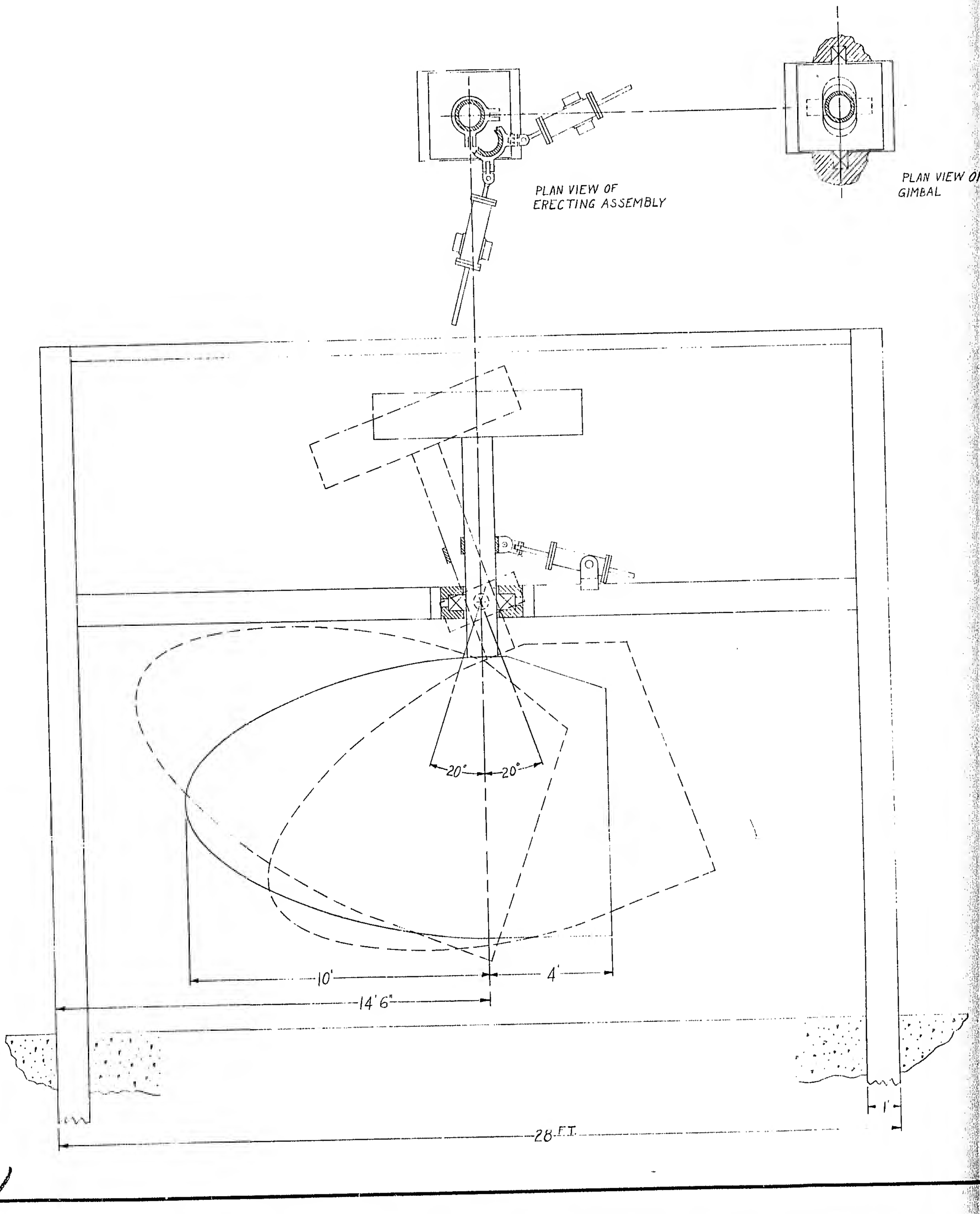
SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

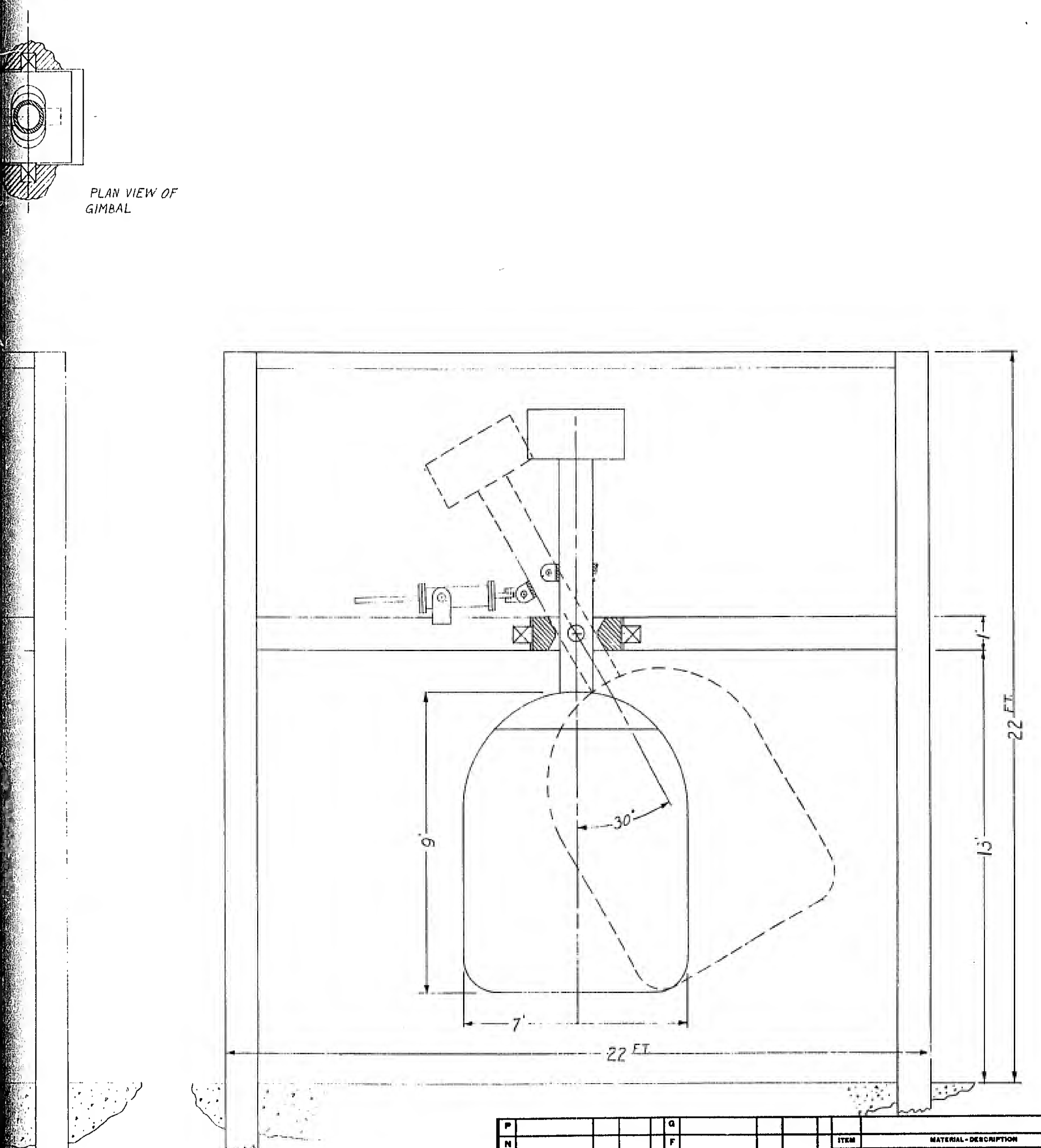
COCKPIT COLUMN CONTROL

SCALE: 2" per FT. DR. TR. CK. APP.

L-37503

D-37504	TOLERANCES NOT OTHERWISE SPECIFIED: DECIMAL ± .005 FRACTIONAL ± 1/64
WO-	





ITEM	MATERIAL-DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

COCKPIT CONTROL ASSEMBLY

SCALE: 1/2" = 1' DR. J. T. Gan Feb 19 '46 TR. CK. APP.

D-37504

	WAS	APP.	DATE		WAS	APP.	DATE
P				G			
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M				E			
L				D			
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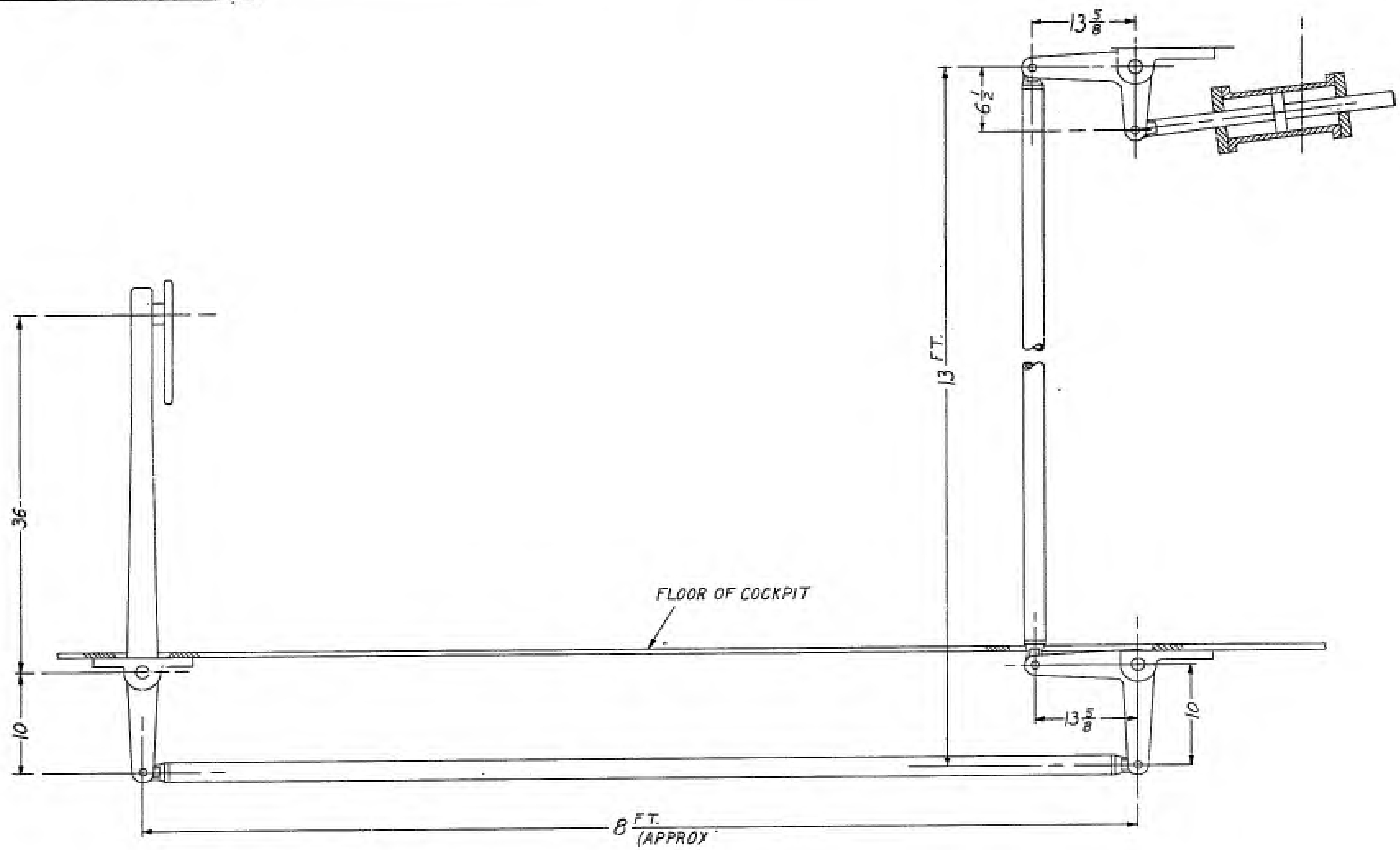
J				B			
H				A	4 PISTONS		Mar 21'46

C-30047
WO-

TOLERANCES NOT OTHERWISE SPECIFIED:
DECIMAL ± .005 FRACTIONAL ± 1/64



ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

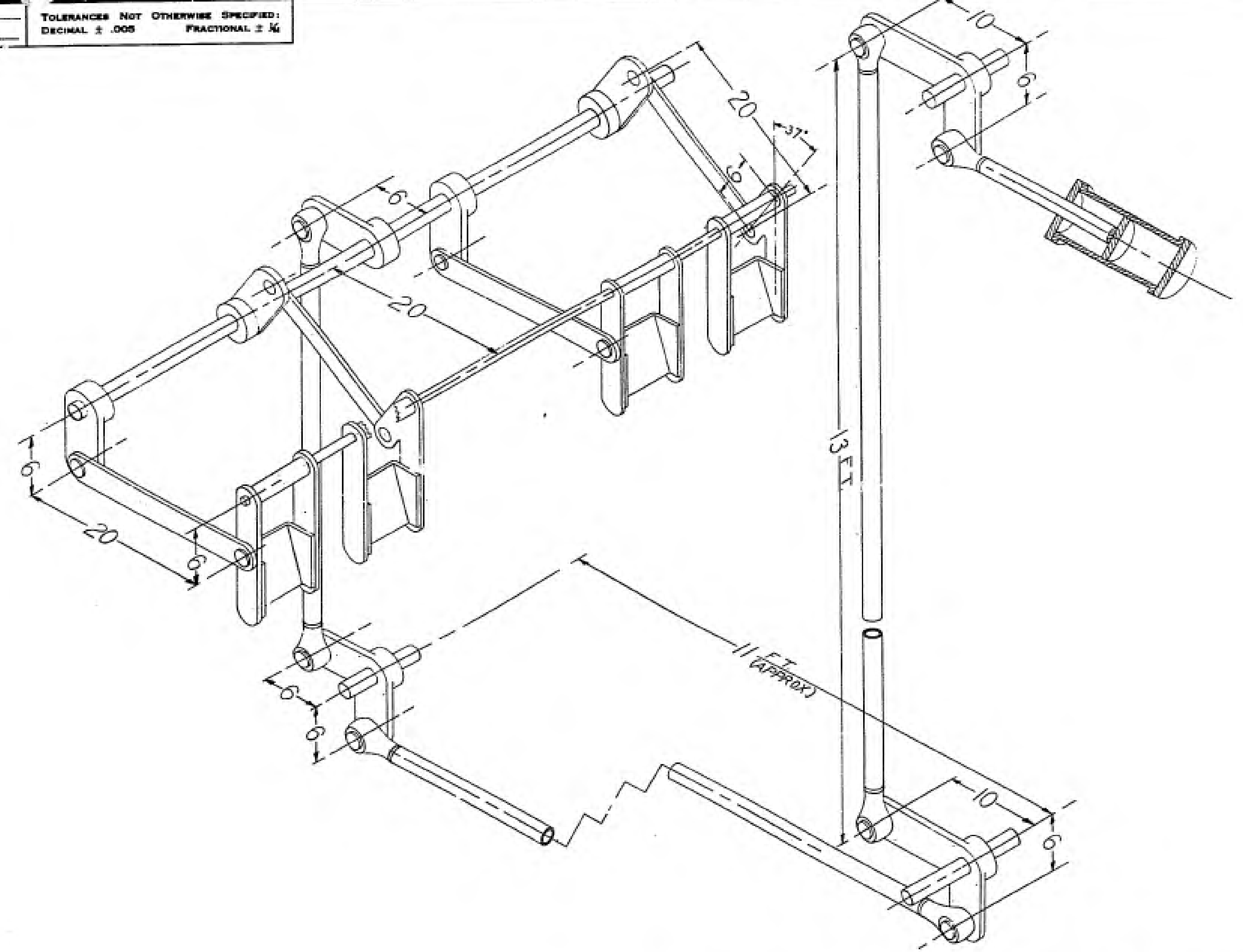
SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

ELEVATOR CONTROL SYSTEM

SCALE: 1/8 SIZE DR. J. T. [illegible]
TR. CK. QR APP. [illegible] 1/18/46

C-30047

C-30048	TOLERANCES NOT OTHERWISE SPECIFIED:
WO-	DECIMAL ± .005 FRACTIONAL ± 1/64



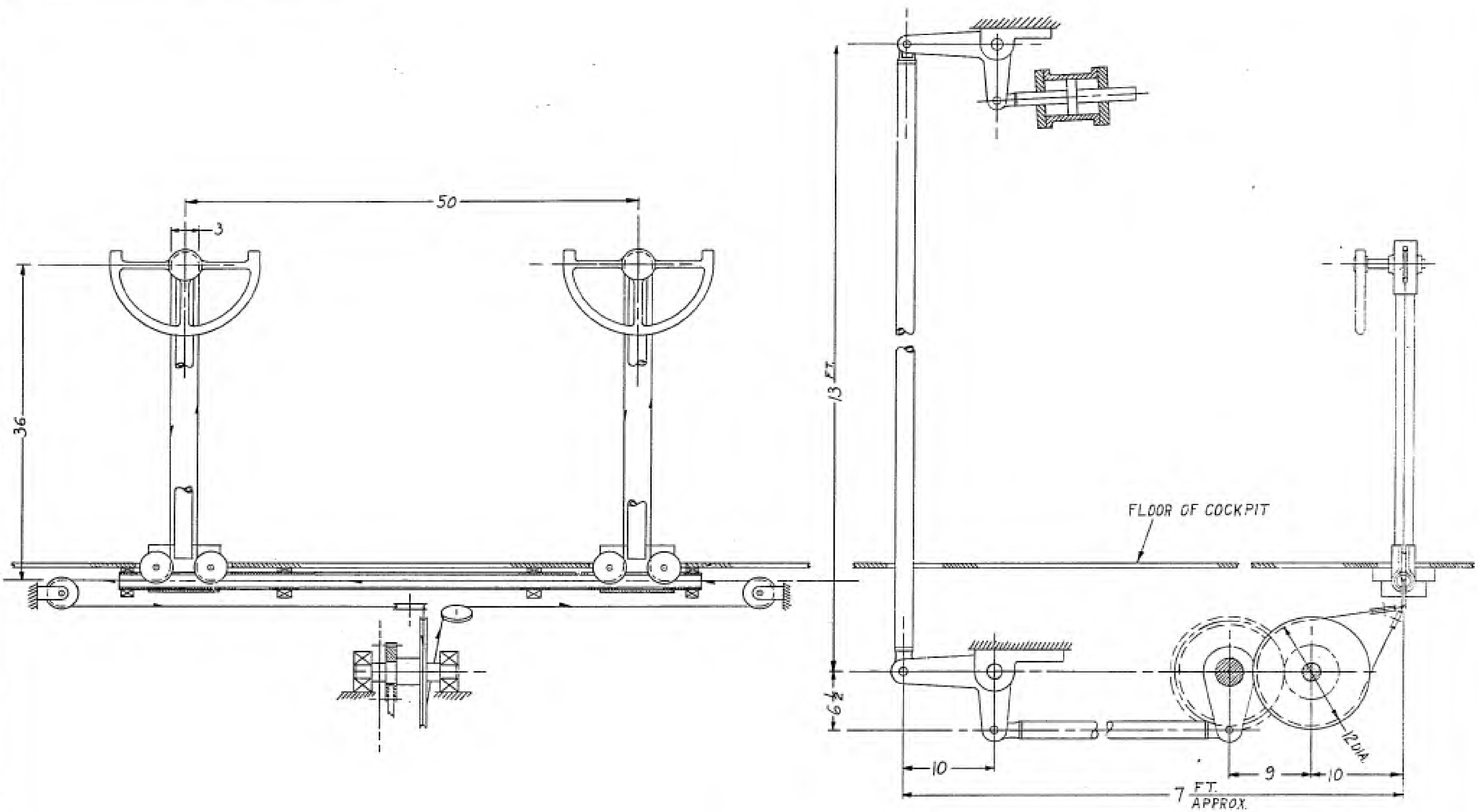
ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

RUDDER CONTROL SYSTEM

SCALE: 1/8 SIZE DR. J. I. Egan, Mar 11, '46 C-30048
TR. CK. CP APP. 4/8/46

C-30049	TOLERANCES NOT OTHERWISE SPECIFIED:
WO-	DECIMAL ± .005 FRACTIONAL ± 1/64



ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

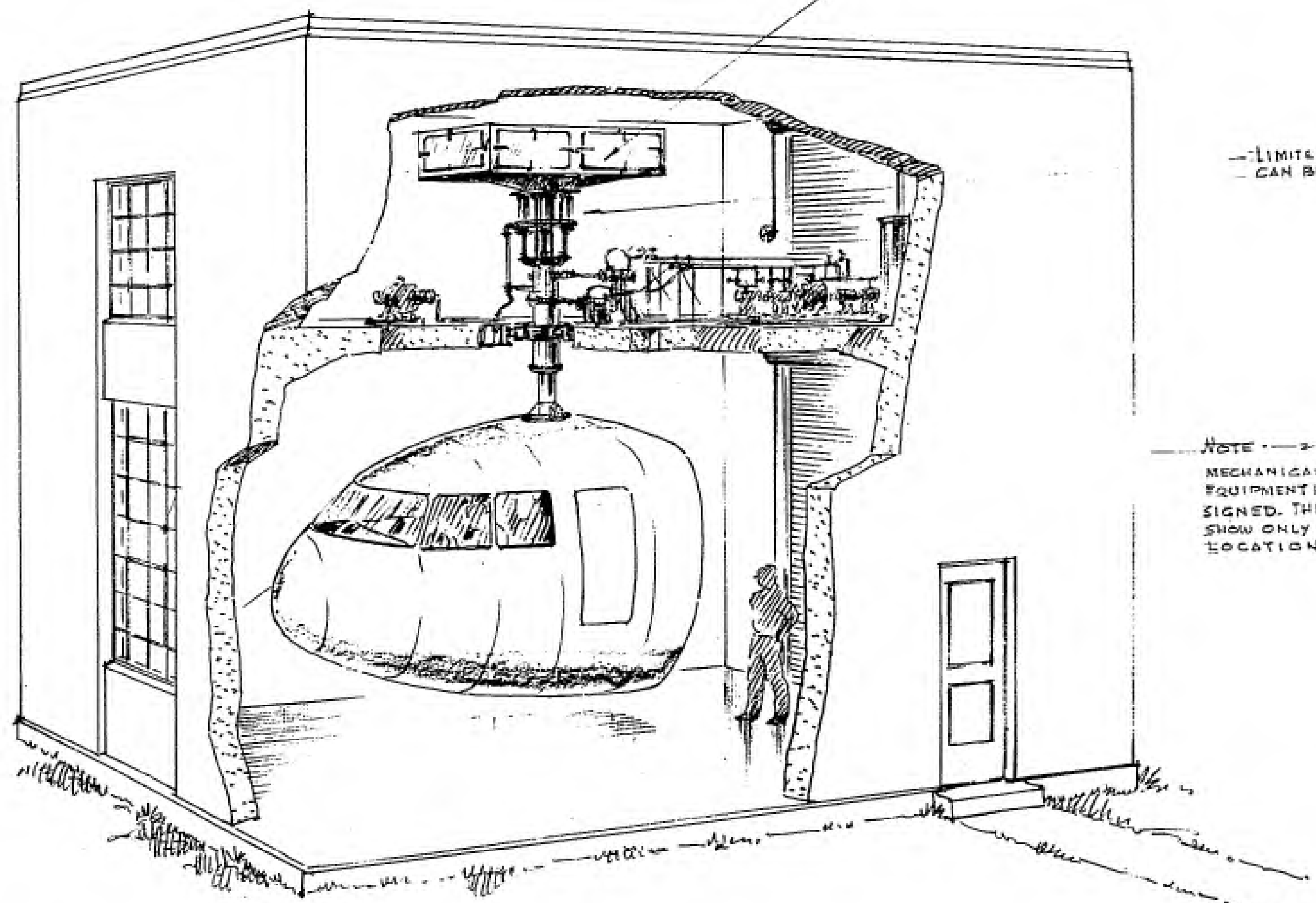
AILERON CONTROL SYSTEM

SCALE: 1/8 SIZE DR. J. Egan Mar 8 '46 CK. ER APP. 4/9/46 TR.

C-30049

C-30053
WO-

TOLERANCES NOT OTHERWISE SPECIFIED:
DECIMAL ± .005 FRACTIONAL ± 1/64



- A·S·C·A COCKPIT MOUNTING -
SKETCH TO INDICATE OVERHEAD MOUNTING

RESTRICTED

ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6345

SCALE: DR. TR. CK. APP.

C-30053

6345
Report No. R-125

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: July 29, 1947

Written by: C. Robert Wieser

Drawing: C-30557

Subject: Flight Simulation, Discussion of

References: Project WHIRLWIND Summary Report No. 1

Introduction

The principal component of the Project WHIRLWIND equipment is an electronic computer. While this computer is a general-purpose device, its first major assignment is the study of aircraft design and performance. The computer, with associated equipment, will become an aircraft analyzer.

The proposed analyzer might be used, as a typical example, to study the characteristics of a proposed aircraft which has never been built. In such a study, wind-tunnel data from a model of the proposed aircraft would be used to furnish the computer with the response characteristics of the plane. In addition to recording the performance of the aircraft, the analyzer must also provide data on pilot reactions and handling characteristics of the aircraft. The preface to the Aircraft Analyzer specifications states that:

"The most significant feature of this analyzer is that the reactions of the pilot to the handling characteristics of the airplane are introduced not as simple responses to given situations but as the more complex responses characteristic of the human being."

It is evident that the environment and "feel" of an aircraft in flight must be simulated as accurately as possible.

Analyzer System

A pictorial schematic view of the analyzer components is shown in attached Drawing C-30557. Provision is made for pilot and co-pilot stations within a cockpit which will contain

the controls and instruments of the aircraft being studied. Control information is transmitted to the computer, which computes the response of the simulated plane to these control inputs. The aircraft's computed response is transmitted back to the cockpit, where it is manifested as

1) forces on controls, (C.F.L.)
2) proper orientation of all instruments
3) simulated noise and vibration
4) simulated acceleration of the cockpit

Simultaneously, the behavior of the aircraft is recorded at the "Output" station.

A more detailed description of the analyzer is set forth in Project WHIRLWIND Summary Report No. 1 issued in April, 1946.

Computer

The computer is of the digital type and uses a binary number system. Information, such as control positions, transferred from the cockpit to the computer must be converted from analogous quantities (probably voltages) to binary numbers. In a like manner, computed binary numbers must be converted to analog voltages before the information can be used to control instruments, noise level, etc., in the cockpit. (This function is performed by the "Digital to Analog Conversion" equipment shown in Drawing C-30557.)

The computer itself is to be capable of solving simultaneously the numerous equations which determine the dynamic performance of an aircraft in flight. A unique feature of the computer is that it will solve these equations in real time; i.e., the speed of solution by the computer must be as rapid as the response of the actual aircraft and pilot.

Cockpit Structure

The interior of the cockpit will have the same appearance as the cockpit of the plane being studied. Pilot and co-pilot stations with all controls and instruments will be installed. Windows will be made translucent so that the pilot is not disoriented by objects outside of the cockpit.

The cockpit will be suspended like a pendulum and will be free to be tilted under power in order to apply acceleration to the pilot.

Instruments

All instruments will be properly oriented as indicated by the computer. The simpler instruments (such as oil pressure or temperature gauges) will probably be voltmeters energized by the computer. The more precise instruments (such as artifical horizon and altimeter) will probably be driven by servomechanisms which receive input data from the computer. Since the required response of these instruments need not exceed the ability of the pilot to follow them, it is felt that proper instrumentation will not involve any problems of a fundamental nature.

Control Force-Loading Equipment

The proper forces on the control column and pedals will be computed by the computer and applied to the controls by hydraulic servomechanisms. Provision will be made for adjustable control damping, Coulomb friction, elasticity, and backlash. On the basis of tests already made on experimental equipment, it seems safe to predict that control force-loading can be simulated satisfactorily.

Noise and Vibration

Satisfactory simulation of noise and vibration has already been accomplished in some of the Navy's Operational Flight Trainers. Vibration will probably be inserted by means of an unbalanced rotating mass coupled to the cockpit, and noise will probably be produced by an electronic oscillator with suitable filters.

Cockpit Acceleration

The above-mentioned problems have been approached by designing equipment which attempts to duplicate the performance of the aircraft. In the case of cockpit motion, this approach can no longer be used since it is not considered feasible to build a cockpit which will have the same degrees of freedom as the aircraft. Also, it is not feasible to build a cockpit which can be subjected to large sustained accelerations since such a device would have to move through very long distances in response to these accelerations. For these reasons, it has been decided to suspend the cockpit, as shown in Drawing C-30557, and produce the sensation of horizontal acceleration by tilting the cockpit.

In such a system the resultant sustained acceleration is limited in magnitude to the acceleration of gravity, or 1g. The only control that can be exercised over a sustained period is control of the direction of the 1g gravity vector with respect to the

pilot's seat. This is to be accomplished by two hydraulic servomechanisms. One will tilt thecockpit as it would be tilted by climbing or diving, and the other will tilt the cockpit as it would be tilted by roll. It is expected that a sustained acceleration of 1/2 g parallel to the plane to the plane of the pilot's seat can be produced satisfactorily.

Since the angle of tilt of the cockpit will control the direction of the resultant acceleration on the pilot, the proper tilt angle will be determined not by the aircraft's attitude alone, but will take into account its lateral acceleration as well. For example, a skid turn in level flight would cause the cockpit to tilt about its roll axis to simulate centripetal forces on the pilot, while a perfectly banked turn would require no tilt since it produces no component of acceleration parallel to the plane of the pilot's seat.

While the control method indicated above provides the correct sustained lateral acceleration, it raises problems in changing the acceleration without severe transient accelerations which would destroy the simulation of aircraft flight. The solution of this problem requires further compromise. If the tilting servos were designed to accelerate the cockpit instantaneously by an amount equal to the difference between the instantaneous required acceleration and the component due to gravitational acceleration, the result would be an ideal acceleration servomechanism. However, such a drive would be undesirable since an ideal acceleration servo is inherently unstable with respect to position; i.e., while the correct acceleration would theoretically be applied at all times, the cockpit would oscillate. In order to prevent oscillation, damping forces proportional to velocity must be applied with an attendant error in accelerating forces.

Another problem involved in the selection of the proper radius between the cockpit suspension axis and the pilot. As the radius is decreased, the motion of thepilot's body approaches pure rotation and angular acceleration; similarly as the radius is increased, the motion of the pilot approaches pure translation with translational acceleration. The latter sensation seems preferable, particularly for the case of large aircraft. However, as the radius is increased, the structural problem of cockpit support becomes increasingly difficult, and the power requirement of the cockpit tilting drives increases. For these reasons it is desirable to keep the radius as small as possible without destroying the illusion of flight.

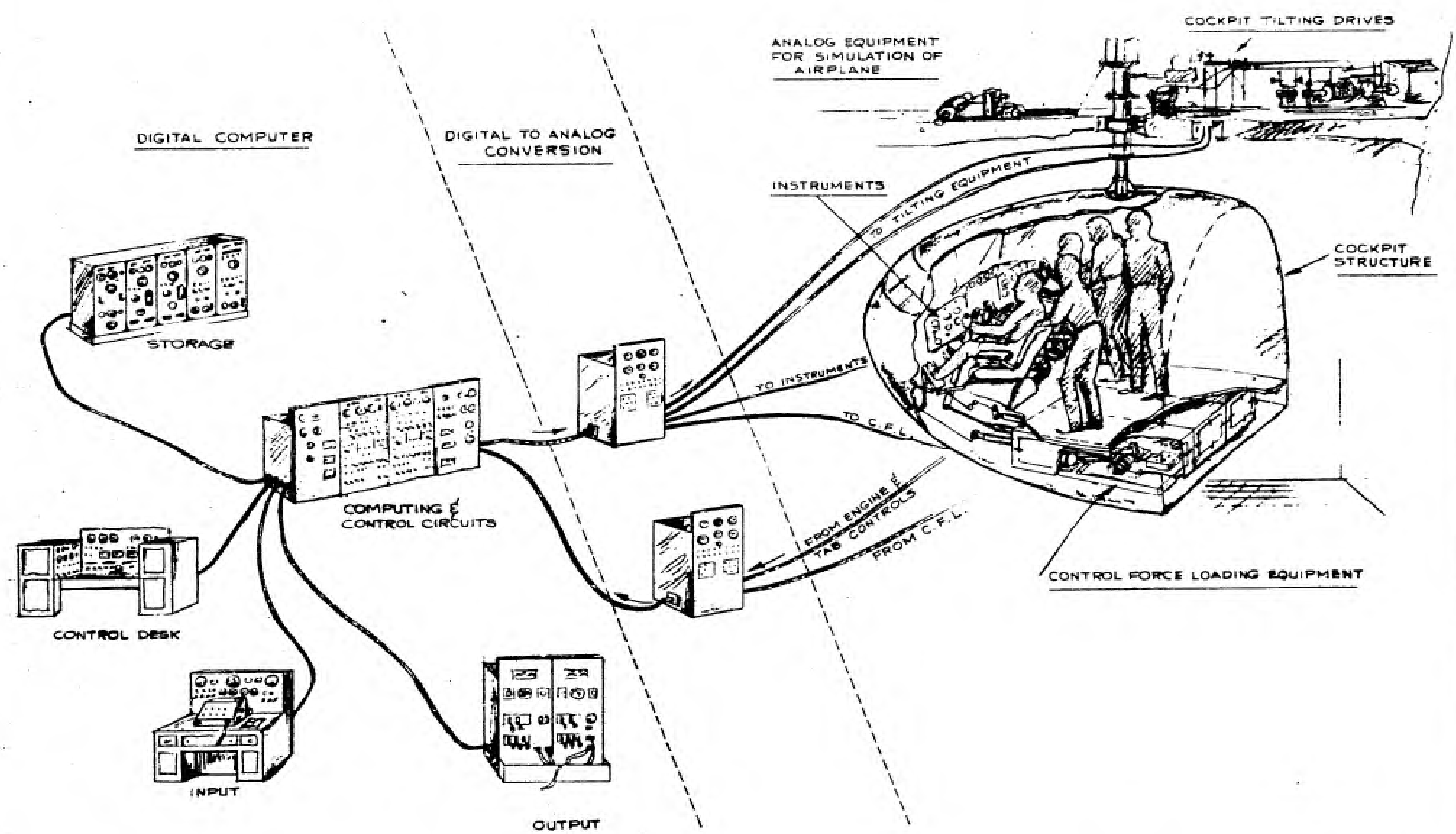
In addition to tilting the cockpit to produce the "feel" of the aircraft's response to the controls, it may be desirable to introduce transient translational accelerations of brief duration and alternating direction to simulate the effects of flight through turbulent air. (Transient forces would be applied simultaneously to the controls.) The value of these transients in simulating flight and the exact manner in which they should be applied have not yet been determined.

Quantitative data on optimum acceleration of the cockpit are difficult to obtain since allowable departures from exact simulation depend on the subjective sensations felt by the pilot. The problem is not confined to the field of engineering alone, but requires knowledge of the physiology and psychology of the pilot's perception and sensation.

Engineer: C. Robert Wieser

Approved: Jay W. Forrester

CRW:has



USED IN G345 REPORT R-125

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT NO. 6345

PICTORIAL TO SHOW RELATIONSHIPS OF COCKPIT COMPONENTS

SCALE: NONE | F.B. 5-26-47 | C-30557

C.R.W.

6295
Report 36

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

Date of Report: May 3, 1945

Schematic: B-40270

Subject: Description of Proposed Control Force Demonstrator

Identification:

The control force equipment represents an important part of the proposed aircraft analyzer. The preface to the BuAero specifications for the analyzer states

"The most significant feature of this analyzer is that the reactions of the pilot to the handling characteristics of the airplane are introduced not as simple responses to given situations but as the more complex responses characteristic of the human being."

The complex human responses mentioned are the result of the composite effect of instrument readings and the forces appearing on the airplane controls. In order that these responses be of value it is of great importance that these control forces be accurate and realistic.

Three separate sets of control forces must be generated--elevator or control column forces, aileron or control wheel forces, and rudder or control pedal forces. All three sets require the same type of generated loads and differ only in magnitude and rate. They present the same problems and can be solved by the same types of equipment. The general discussions which follow apply to all controls, but specific values refer to elevator or control column forces.

A system for generating control forces has been devised, and a test setup or demonstrator is being built to check the worth of the system. This report will outline the problem and discuss the reasons for choosing the system to be tested. This discussion will be followed by a description of the test setup giving numerical values for all constants.

References: 6295 Reports Nos. --

4	Two Phase Induction Motors -- Characteristics as torque motors
6	Throttle Valve
13	Strain Gauges for Control Force Measurement
22&29	Summing Amplifiers
33	Tachometers
37	Stability & Gain of Proposed CFD
38	Further Analysis of CFD
39	CFD, Time Schedule for Completion
41	Strain Gauge Preamplifier

Discussion:

I. Proposed Solution

The problem falls into two categories:

(1) The translation of computed data in the form of an electrical signal from the analyzer into torque or load forces on the controls.

(2) Creation of the proper "feel" in the action of the controls.

The controls in an airplane consist of a column, wheel, or pedals, having inertia and friction. The controlling member is connected by elastic connecting cables to a set of control surfaces having inertia and friction. Assuming no aerodynamic load on the control surfaces, the control system can be shown schematically as follows:

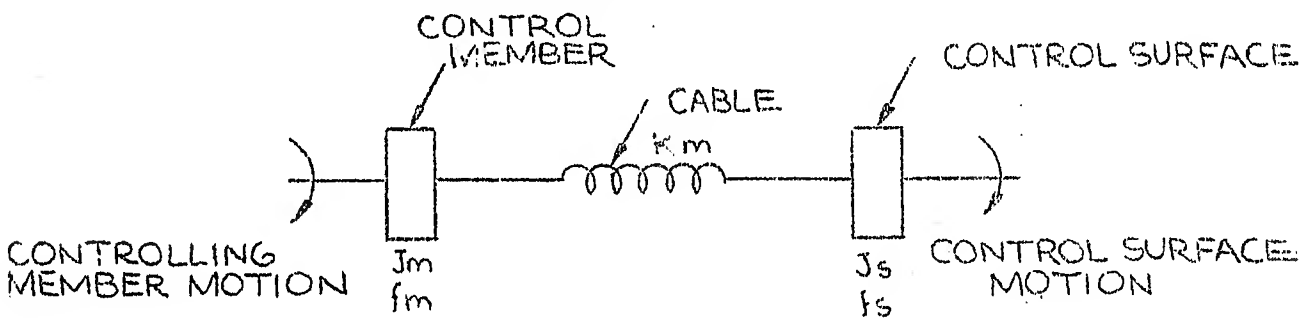


FIGURE 1. AIRPLANE CONTROL WITH ELASTIC CABLE

This system is not a simple one to approximate. In addition, the elasticity of the cables is probably an unnecessary refinement. If the elasticity of the cables is neglected the system becomes

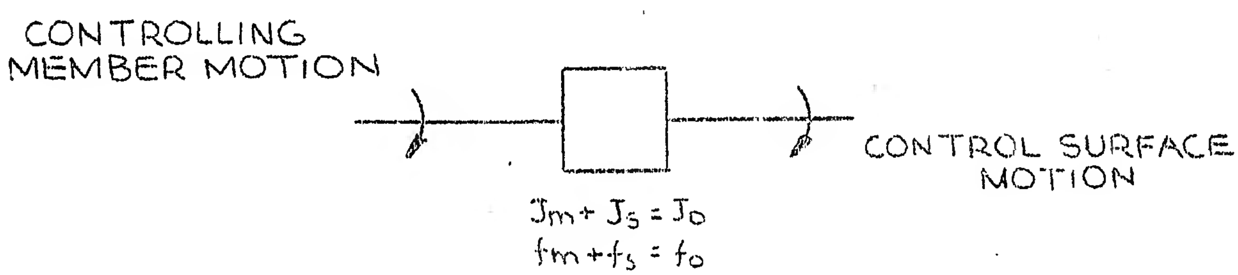


FIGURE 2. AIRPLANE CONTROL WITH INELASTIC CABLE

J_o is the combined inertia of the system referred to the pilot. f_o is the combined damping, both viscous and coulomb. There is no elasticity, and the system exhibits no oscillatory tendencies. The inertia and damping will both

vary depending on the airplane. In particular, the viscous damping due to motion of the control surfaces will depend on the configuration of these surfaces.

The aerodynamic load on the control surfaces is largely a restraining force proportional to control surface deflection. This force is the only one considered in the specification equations at the present time. It is also possible that there may be additional effects such as changing damping or even higher order effects. For the time being only the proportional restraining force will be considered.

Such a force is equivalent to a spring to ground connected to the control surfaces. The new system will be

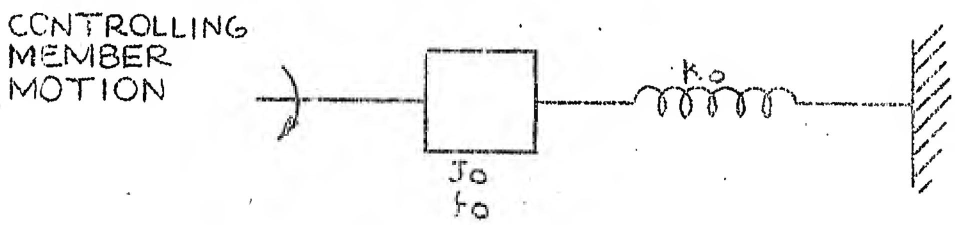


FIGURE 3. AIRPLANE CONTROL SYSTEM WITH AERODYNAMIC LOAD

The value of k_o is computed by the analyzer and is dependent on airplane characteristics and flight conditions.

The problem then falls into the two separate divisions mentioned above.

(1) Obtaining an effective force tending to return the control to neutral. This force must be proportional to the control displacement from neutral and must vary in magnitude according to an electrical signal from the analyzer.

(2) Devising a system that will allow adjusting J_o and f_o over reasonable limits; that is, a system which will have the proper "feel".

Additional control details, such as translation of control and tab positions into electrical data for the analyzer are not part of the control force problem.

II. General Approach to the Problem

Generation of control forces requires first a controller which will develop a force or torque which is accurately proportional to an input signal. Such a controller is a prime requisite for any loading system and will be discussed in a separate section. A simple controller system would be

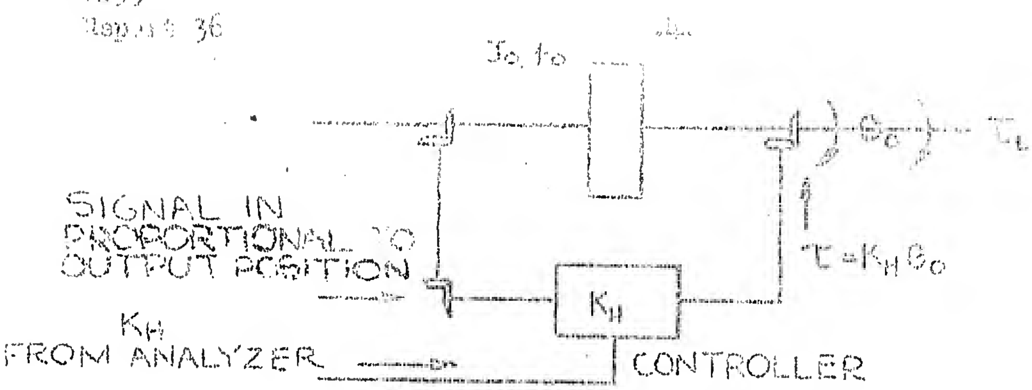


FIGURE 4. SIMPLE CONTROL FORCE SYSTEM

Such a system would have the same characteristics as the system of Figure 3. The controller constant can be varied either in the controller or by attenuating the input to the controller. The only means available for varying J_o and f_o is actual physical change of the mass and friction. There is a limit to this method of varying the constants, however. It is simple to increase inertia by adding weight to the column but troublesome to do so in a neat and unobtrusive manner. There is no way of reducing inertia below the designed minimum. Viscous dampers are large, power consuming, not easily variable, and do not maintain their calibration. Coulomb dampers are relatively simple.

A method is therefore needed that will enable reasonable changes in effective inertia and damping to be made. One method is to add components to the controller input that are proportional to the first and second derivatives of the output or control motion.

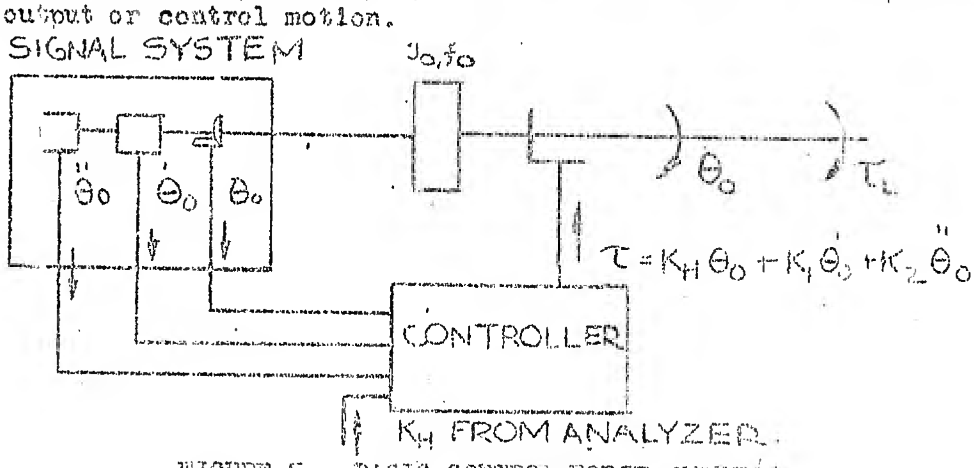


FIGURE 5. BASIC CONTROL FORCE SYSTEM

It is unimportant to the output member whether the torques on its shaft come from the inertia forces and damping forces associated with it or from the controller. $K_1\dot{\theta}_o$ will have the same effect on shaft performance as would a viscous damper with damping $f = K_1$. $K_2\ddot{\theta}_o$ will have the same effect on shaft performance as would a mass of inertia $J = K_2$. Since it is possible to change the signs of K_1 and K_2 it is possible to either increase or decrease the "effective" inertia and damping associated with the output member or control. A system of this type should be able to simulate exactly the characteristics of the simplified airplane control system of Figure 3.

III. Choice of Elements

A. Controller

Requirements

The controller described above has the following requirements:

1) It must produce torques which are proportional to input signals (probably a-c voltages).

2) It must be capable of developing torques of sufficient magnitude.

3) It must be capable of developing velocities of sufficient magnitude.

4) It must have a high speed of response.

In greater detail these requirements are

1) Accuracy

No very high degree of accuracy is required. Technically, of course, the accuracy of the controller; that is, the consistency of the torque to signal ratio, will determine the ability of the device to represent the ideal mass-spring-damping system of Figure 3. Actually, it will be beyond the ability of the operator to distinguish a difference from ideal torque of probably 10% or more. The frequency response and transient characteristics of the system will also vary with controller accuracy, but these responses are not important over fairly broad limits. Errors of 10% can probably be tolerated without appreciable effect on pilot "feel".

2) Maximum Torque Required

Two pilots of normal strength under normal conditions can exert a pull on the control column of up to 600 pounds according to NACA tests. To this figure must be added an adequate factor of safety to allow for pilot responses to unusual conditions. 1000 pounds has been taken as a desirable maximum available force to cover all conditions. This does not mean that the maximum control forces possible in an airplane are less than 1000 pounds; they may be considerable more, but there is no point in having available forces which the pilots cannot exert.

3) Maximum Velocity Required

No data was available on this important point. An estimated value of 5 ft/sec. was obtained, however, by the following method and is felt to be of the proper order.

An approximate sinusoid was generated by R. Everett by simply moving his hand as if stroking a control column. No load forces were assumed;

the maximum amplitude was about 16" and the period was such as to give a high but maintainable rate. The resulting period was about .8 seconds and the maximum rate based on assumed sinusoidal motion was 5 ft/sec. In the actual equipment the pilot will have to move the mass of the column and work against the system friction and control surface restraining torque. 5 ft/sec. should be adequate for even quick pulls against these loads.

The above sections prescribe a maximum force of 1000 pounds and a maximum velocity of 5 ft/sec. If both maximum force and maximum velocity occur at the same time the controller must develop over 9 HP. Such power is beyond the instantaneous output of two men, especially when pulling with their arms only. The continuous power output of a man is low--perhaps .1 HP. His overload capacity is quite high, however--perhaps 1 to 2 HP (for very short times) depending on conditions. The maximum horsepower required of the controller in order to overcome pilot torque will, therefore, be nearer 3 HP than 9 and then only for short times. In addition, the controller must supply enough power to accelerate the controller mass when travelling at maximum rates. The maximum desired acceleration and the system inertia must also be considered if the true maximum required controller power output is to be determined. Due to the physical nature of the controller eventually chosen the true power output was not computed.

B. <u>Basic Controller Decisions</u>

The type of controller could be either air, electric, or hydraulic. Air was discarded without discussion largely because of lack of available equipment and technique although considerable difficulty could be forseen in the use of an air controller.

An electric controller was considered but discarded. The forces and horsepowers required are of such magnitude that they could be obtained only by a large electric motor well geared down. Under these circumstances the inertia and friction referred to the controls become of absurd magnitude.

A hydraulic controller presented the most possibilities because of the high power and speed of response of hydraulic systems. A controller proposal using a hydraulic motor geared to the control column was discarded because it suffered from the same difficulty as the electric system although to a lesser extent. A hydraulic cylinder and piston was finally decided on as most nearly meeting the conditions. Reflected inertia and friction are at a minimum due to absence of gearing while a wide range of forces and speeds are available with proper choice of piston area, control pressure, and lever arm.

With the force producing element decided on there remained the choice of a pressure controlling device. A simple form of the method chosen is shown in Figure 6.

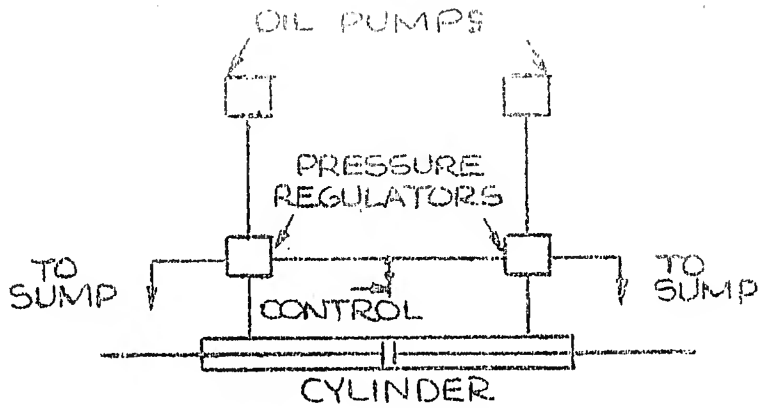


FIGURE 6. HYDRAULIC CONTROLLER

The control device continuously adjusts the regulator settings to give the desired pressure differential across the piston. In the interests of high speed of response, a single stage partially balanced regulator was designed.

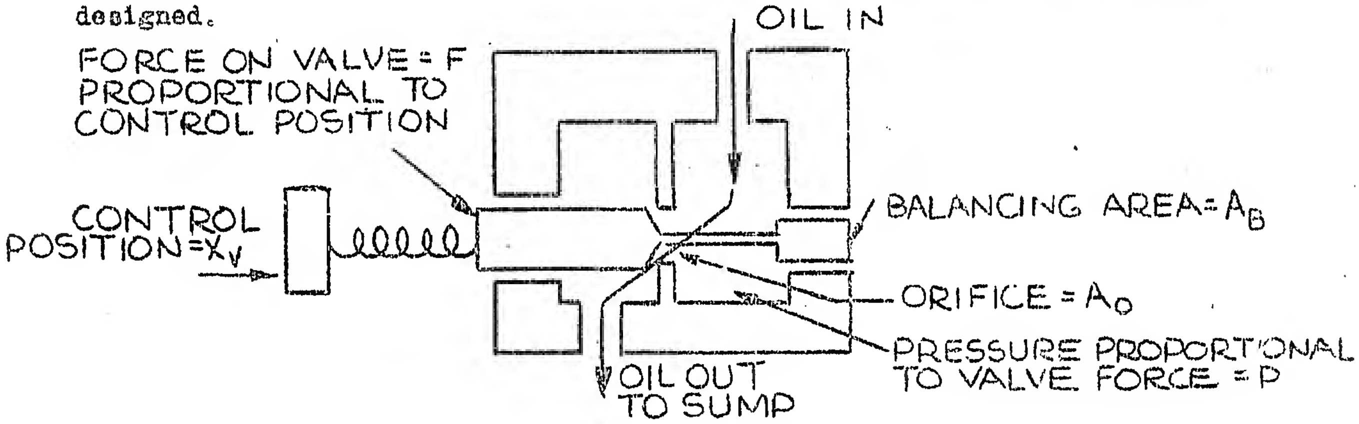


FIGURE 7. PRESSURE REGULATING VALVE

The force on the valve is given by the equation

$F = P(A_o - A_B) = KX_v$ where quantities are shown in Figure 7.

The assumption is made in this equation that the velocity of approach to the orifice is negligible. In other words, the pressure head of the oil against the valve is assumed to equal the pressure head of the oil back in the low flow area. If this assumption is fair for the flow rates concerned, then the valve calibration is independent of flow. Such is the case for a valve of the size finally decided on.

A system has now been obtained which enables a position to be converted into a force. It only remains to obtain a method of obtaining a position from a voltage.

A two-stage converter was chosen. The first stage consists of a 2-phase a-c torque motor driven from a power amplifier.

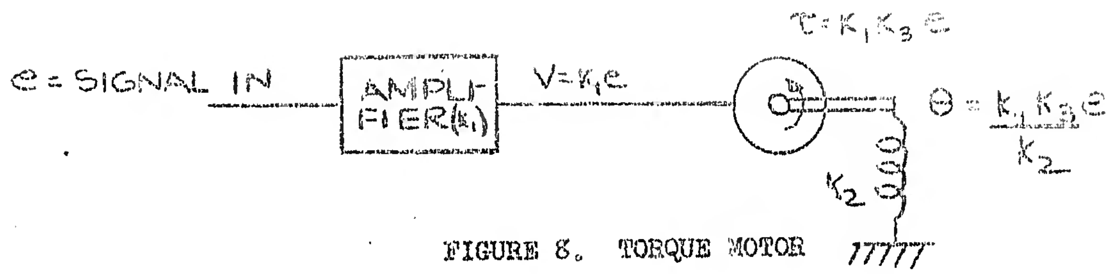


FIGURE 8. TORQUE MOTOR

The low power signal in (e) is linearly amplified in amplifier (k_1). When applied to the torque motor control field this voltage results in a proportional torque (k_1k_2e). A restraining spring turns this torque into an angular position of the torque motor arm.

Unfortunately, the power level of the torque motor is insufficient to drive a pair of balanced pressure regulator valves of the type described above. The torque motor position is therefore amplified in a simple hydraulic preamplifier.

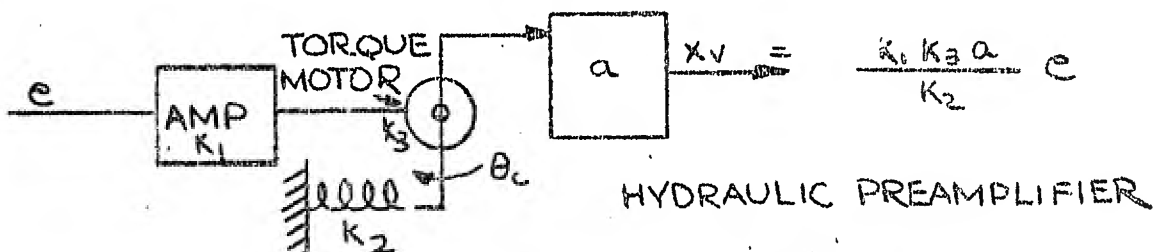


FIGURE 9. TORQUE MOTOR AND HYDRAULIC AMPLIFIER

The hydraulic preamplifier can be built to give a reasonably high power level for driving the pressure valves.

The controller is now complete in essentials. See Figure 10.

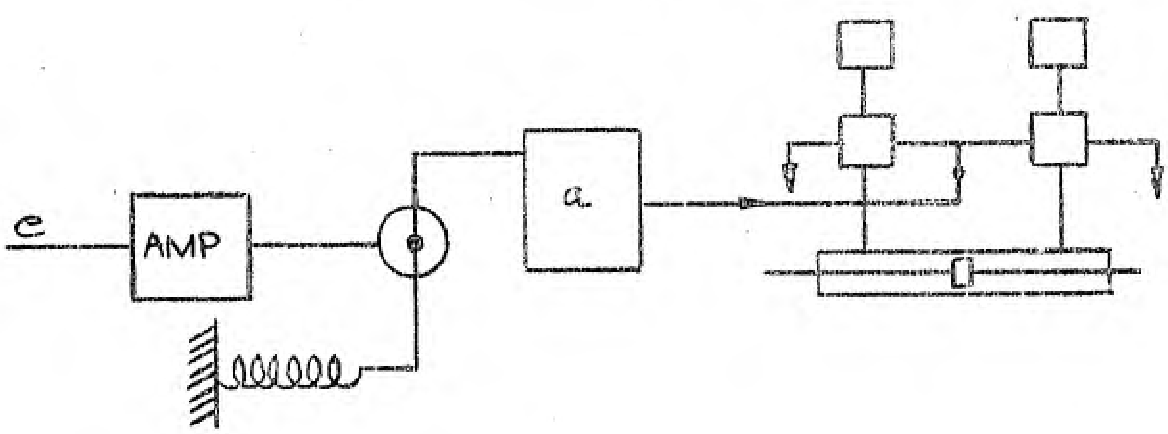


FIGURE 10. COMPLETE CONTROLLER SCHEMATIC

Two important matters remain to be settled.

1) The nature of the oil supply pumps.

When the control column is standing still no oil is required from the supply except for leakage. The maximum amount of oil required depends on the maximum speed of the piston. It is possible to use either a variable displacement supply or a fixed displacement supply. The fixed supply is far simpler but has a number of disadvantages.

With the fixed supply normal pump flow is determined by maximum required piston velocity. Standby losses are thus determined by maximum requirements and are much higher than with a variable displacement supply. Total horsepower requirements are determined by the product of maximum force and maximum velocity regardless of whether or not they can occur together. The horsepower requirements of a variable displacement supply are dependent solely on the maximum horsepower required from the controller.

The added complication of the variable displacement supply more than outweighs its advantages, however. Such a supply would be far more expensive and complicated than the constant displacement one. Another servo of considerable power would be required to stroke a large unit, and considerable complication would be needed in a data system for adjusting stroke to correspond to piston speed. The saving in maximum horsepower and in standby losses might be 50% or more, but until experimental evidence is available the added complication does not seem warranted.

Fixed displacement pumps were therefore chosen.

2) Accuracy

The system set up in Figure 10 depends for accuracy on the excellence of a number of units in cascade. Relatively high degrees of perfection are required for each component if the overall error is not to exceed 10%. A solution to this problem is to make a torque servo out of the open cycle torque controller. The loop could be closed as follows:

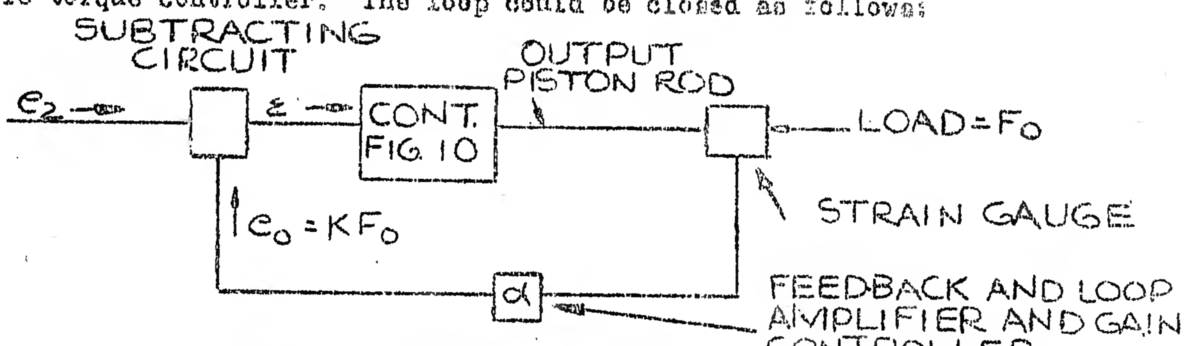


FIGURE 11. TORQUE SERVO CONTROLLER

The strain gage allows use of a feedback voltage proportional to output force. The controller gain would have to be increased to maintain the controller calibration. The overall controller error would decrease. The controller could be made to have as great static accuracy as desired (within the limits of strain gage and summing circuit) by proper adjustment of feedback and controller gain. This refinement requires further study before a decision can be made.

No discussion has been made above as to the transient response of the controller or the effect of adding a feedback signal, except to state that the components have been chosen with a view to making the speed of response as high as possible. This problem is discussed later in this report and more completely in 6295 Reports 37 and 38.

C. Feedback system

Requirements

The controller has been discussed above. The signal system, which will complete the control force load equipment, has the following requirements:

1. All signals must be phase sensitive.
2. Maximum to minimum signal ratios should be at least 100:1 for all elements except the positional signal which should have at least a 500:1 ratio.
3. The dead zones must be kept to a minimum in all elements.
4. The time constants of all signals should be as small as possible.

The Positional Signal

The positional signal can be most easily obtained from a center-tapped potentiometer. A high impedance wire-wound potentiometer should have enough turns to provide adequate sensitivity and be sufficiently accurate for the purpose. Varying the supply voltage to this potentiometer is equivalent to varying the gain of the positional signal to the torque controller and therefore provides a simple means of supplying k_0 data from the analyzer. See Figure 5.

The First Derivative Signal

This signal, which is proportional to the first derivative of output position; that is, output velocity, can be most easily obtained from a commercially available a-c drag-cup tachometer. These tachometers deliver an a-c output voltage proportional in magnitude to the tachometer speed. Various models are available which have different accuracies and residual voltages. The best available will be used.

The Second Derivative Signal

This signal must be proportional to the acceleration of the control member. It is more difficult to obtain than the other signals. There are two general methods:

1) Direct

Acceleration is measured by the lag of a mass behind a driving

shaft to which the mass is coupled by a restraining spring. Such an accelerometer has been constructed in the laboratory but is not very well suited for this use. The inertia of the unit is high and in order to obtain adequate output signals it would have to be well geared up. The reflected inertia would then be high. In addition, the maximum to minimum voltage ratio is lower than desired. A considerable period of development would be required before a satisfactory unit could be obtained.

2) Velocity derivative

A second and more promising possibility is to take the derivative of a velocity signal. The velocity signal can be obtained from another tachometer like the one used for the first derivative or even from the same tachometer if the saving in equipment is worth the necessary circuit complication. The signal from such a tachometer is a modulated a-c voltage, the envelope of which must be differentiated in order to obtain the acceleration signal. Two methods present themselves:

a) D-C derivative

The derivative of a d-c voltage may be taken easily with an R-C circuit. Difficulty arises in that the modulated signal from the tachometer must be first demodulated using a phase sensitive rectifier circuit, then differentiated, and finally remodulated. A complicated circuit results. The problem of ripple voltage, filter time delays, derivative circuit attenuation and time delay, and balanced modulator performance point to a considerable program of investigation. The advantage of such a circuit is that it should produce good outputs for low input rates. The use of 400 cps for the tachometer voltage would improve the time delay troubles but not remove them.

b) A-C derivative

The derivative of the envelope of a modulated a-c voltage may be taken by using a parallel-T network. Such a network provides a satisfactory derivative without carrier phase shift over a sufficient range of modulating frequencies to suffice for this application. It can be connected directly to the tachometer output but would probably require an amplifier stage following to bring the signal level back to the proper magnitude. For high and moderately high accelerations the circuit should work well. For very low input rates network unbalance and harmonic content of the input might be very troublesome. Some input signal will feed directly through the filter and must be compensated for by an opposing tachometer signal. The greater simplicity of this method over the d-c derivative method warrants its study first.

3) Second derivative of position

There is little merit to this method. The signal from a good tachometer is probably superior in quality to that from a derivative circuit, especially as the potentiometer signal is not smooth but stepped. The added complication of two derivative circuits with their cumulative troubles is preferably avoided.

Summation of signals

The means for obtaining the three signals needed have been chosen. It remains to add these signals in a summing circuit and to supply the sum to the torque controller. Variable attenuators will be needed in each signal to the summing circuit to allow proper selection of the magnitude of each signal. Means must also be provided for varying the voltage across the positional potentiometer since this will be the means for supplying analyzer data to the system.

The complete system

A schematic of the complete system consisting of the torque controller and feedback system described above will be found in Figure 12, Drawing B-20270.

IV. The Demonstrator

The demonstrater is a piece of experimental equipment designed to test the validity of the conclusions outlined above. It represents a single axis of the airplane controls; namely, the elevator motion. Using available equipment wherever possible the demonstrator adheres closely to the proposed design. The equipment with associated equations and numerical values is described in some detail below.

General description

The equipment is mounted on a base made up of 6x6 steel H beams and 3/8" plate and is about 9 feet long and 30 inches wide. The operator sits in a metal seat from a Navy 40 mm. gun mount. Oil supplies, valves, force cylinder, control column, output gear box, and miscellaneous fittings are mounted on machined pads welded to the top plate. Electronic equipment is mounted in an open relay rack separate from the base.

Main oil supply

In view of the high powers involved a 2000 psi oil supply was decided on. Flow requirements were determined from the constant power relation.

$$PQ = FV \qquad \text{where } P = \text{max. press.} = 2000 \text{ psi}$$

$$Q = \frac{FV}{P} \qquad Q = \text{max. flow}$$

$$= \frac{1000 \times 60}{2000} \qquad F = \text{max. force} = 1000 \text{ pounds}$$

$$= 30 \text{ cu in per sec} \qquad V = \text{max. velocity} = 60 \text{ in/sec.}$$

$$= 1800 \text{ cu in per minute}$$

$$= 7.8 \text{ gallons per minute}$$

The units purchased were Vickers 2-stage vane pumps of 2000 psi maximum continuous pressure rating and flow rating of 8 GPM at 0 psi and 7 GPM at 2000 psi -- Vickers #V-2305-C. A pair of these were obtained mounted on a 10 HP drive motor. 10 HP was an adequate rating for intermittent duty with one pump at full load and the other idle.

Force cylinder

A cylinder was available from another project. The effective piston area is 2.33 sq. in. and the length of stroke adequate for any need.

Torque motor

A Diehl 2-phase servo motor Model #FPF-49-5 is used as a torque motor.

Hydraulic amplifier

A stroke control assembly from a previous project was modified by removing all special linkages and limit stops.

Pressure control valves

The pressure control valves are of special design. An early model is discussed in 6295 Report #6. Tests on the valve actually used will be covered in a future report.

Electronic Equipment

Summing amplifier

The summing amplifier is of a standard 6295 design discussed in 6295 Reports 22 and 29. Cathode follower inputs are used with variable potentiometers as the cathode resistors to obtain variable gain. Five inputs are used to provide for position, velocity, and acceleration inputs plus provision for strain gauge feedback and the insertion of an external signal for test purposes.

A-C derivative circuit

A parallel-T network tuned to reject 60 cps is used. The output is amplified before insertion in the summing circuit. Harmonic filters will be added if needed.

Strain gauge

A Ruge resistance bridge type strain gauge is affixed to a test section of the control column. The gauge does not measure controller torque output but rather controller torque output less the inertia forces due to that part of the system which lies between the gauge and the piston. The major item excluded is the gear train, but the errors should be small.

The strain gauge produces voltages from 20 microvolts to 20 millivolts. A preamplifier stage is provided near the gauge to raise these small signals to a safe level, and an amplifier in the electronic rack amplifies them for the summing circuit or for measuring purposes.

Torque motor amplifier

The amplifier is provided with a parallel-T input which allows the addition of considerable lead. The purpose of adding lead is not to improve the torque motor performance (already fast enough for this system) but to counteract the time delay of the hydraulic amplifier. Gain potentiometers are readily available for adjustment of amplifier proportional gain and lead time constant.

The output stage consists of parallel push-pull 6L6's capable of delivering about 45 volt-amperes to the torque motor.

Output gear train

The output gear train consists of four 20,000-ohm GR wire-wound potentiometers running at the same speed plus two tachometers running together at a higher speed. At present the train is designed for Kollsman #776-02 drag-cup motors used as tachometers, but Arma #5-1 Induction Generators will probably be used. Gear ratios and speeds for the system are given below.

Quantity	Ratio	Maximum Speed
Control handle	Lever arm = 26"	60 in/sec
Piston	= 5.2"	12 in/sec
Control Column	X 1	20 RPM
Potentiometers	X 6.85	137 RPM
Tachometers	X 123.4	2500 RPM

The performance of the separate components of the Control Force Demonstrator are described in detail in 6295 Report #37. Equations are derived for component performance and numerical values given for all constants. Report #38 describes the stability and frequency response for the complete system and discusses possible ranges of operation.

Written by R. W. Evens

Approved Jay W. Forrester

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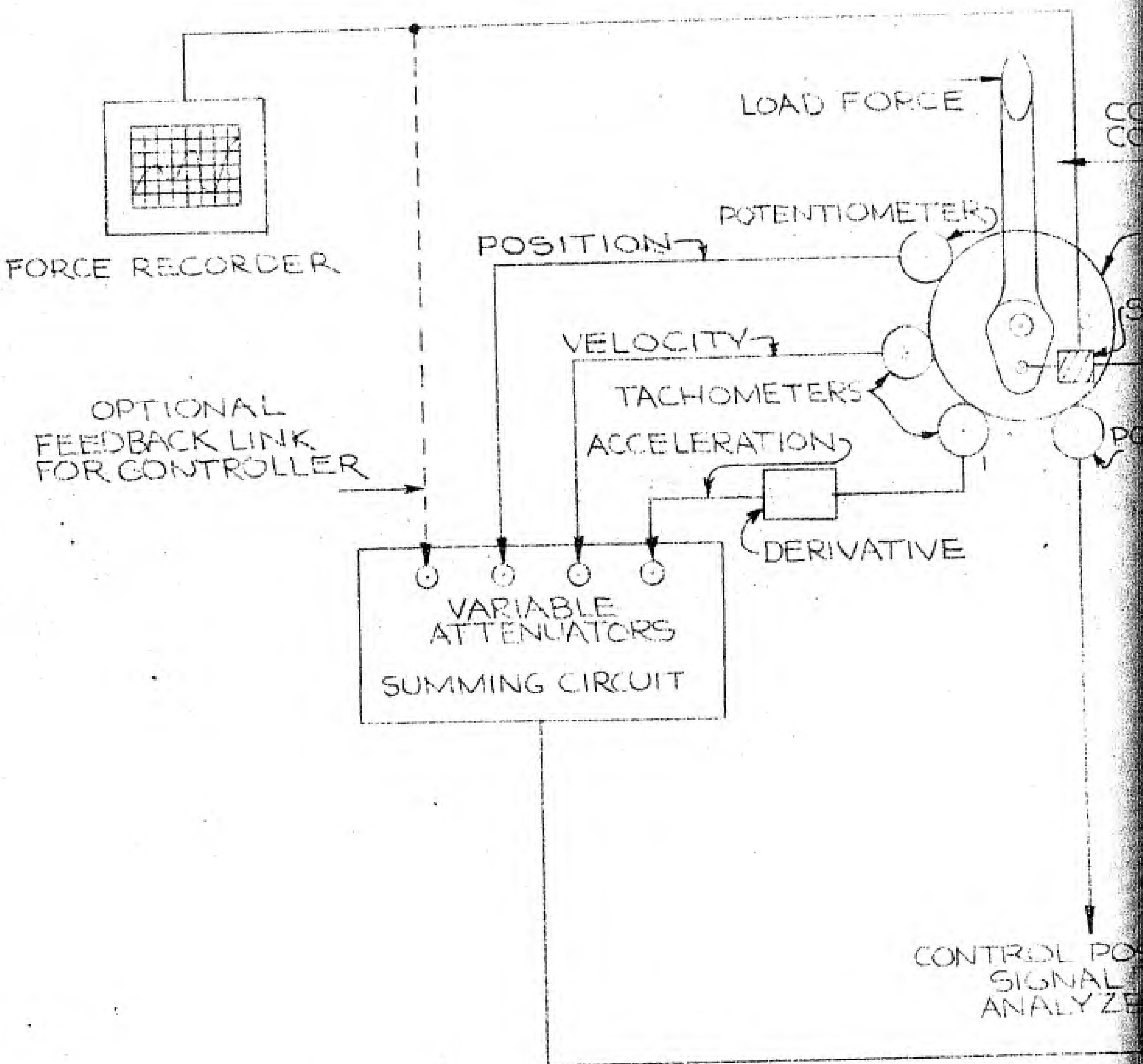

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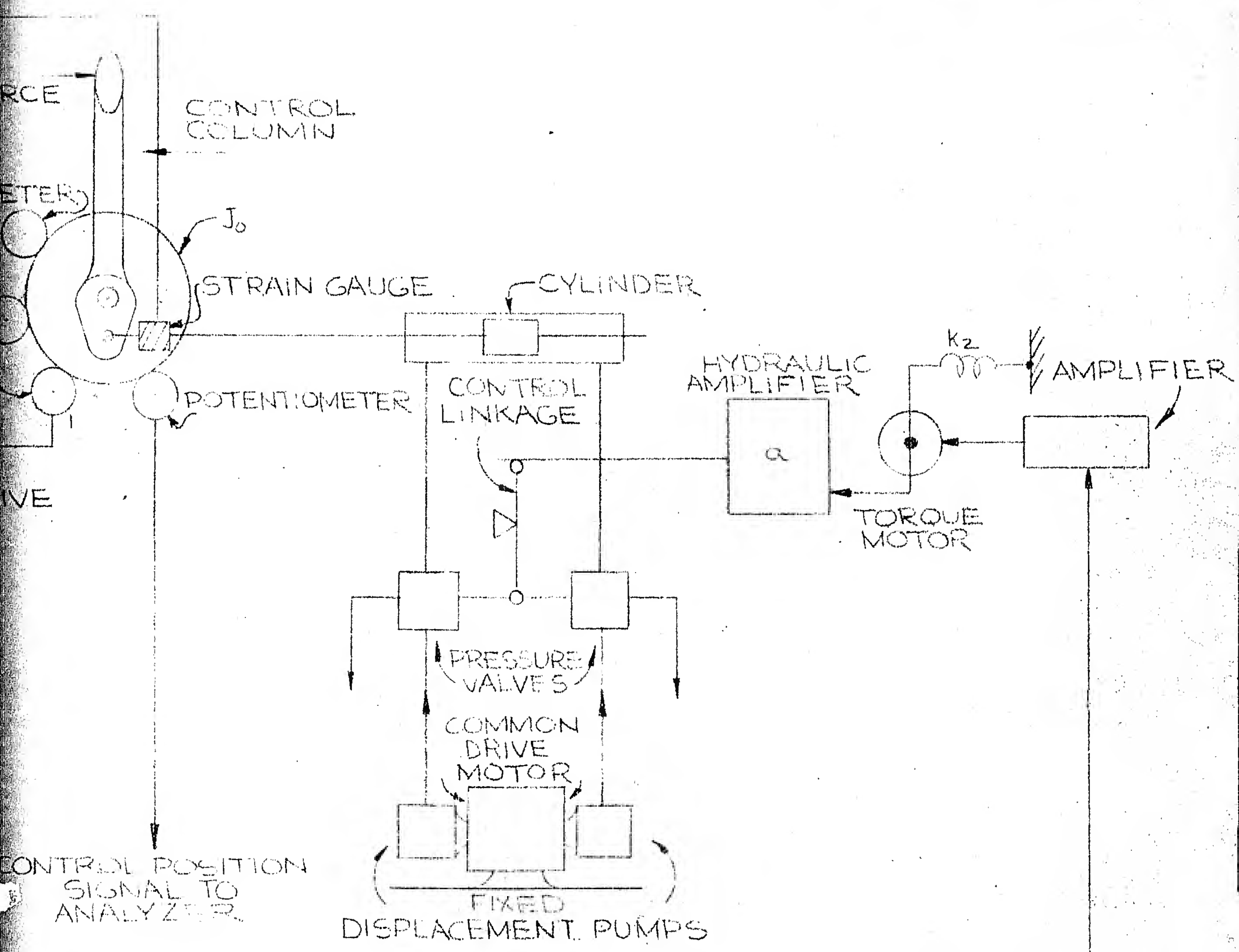

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ITEM	MATERIAL - DESCRIPTION	PART NO.	QUAN.

SERVOMECHANISMS LABORATORY OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DIVISION OF INDUSTRIAL COOPERATION PROJECT NO. 6295

COMPLETE CONTROL FORCE SCHEMATIC

SCALE:	DR. EPH 4/27/45	
TR. TL 4/28/45	CK. REE 4-30-45	APP. 4/30

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